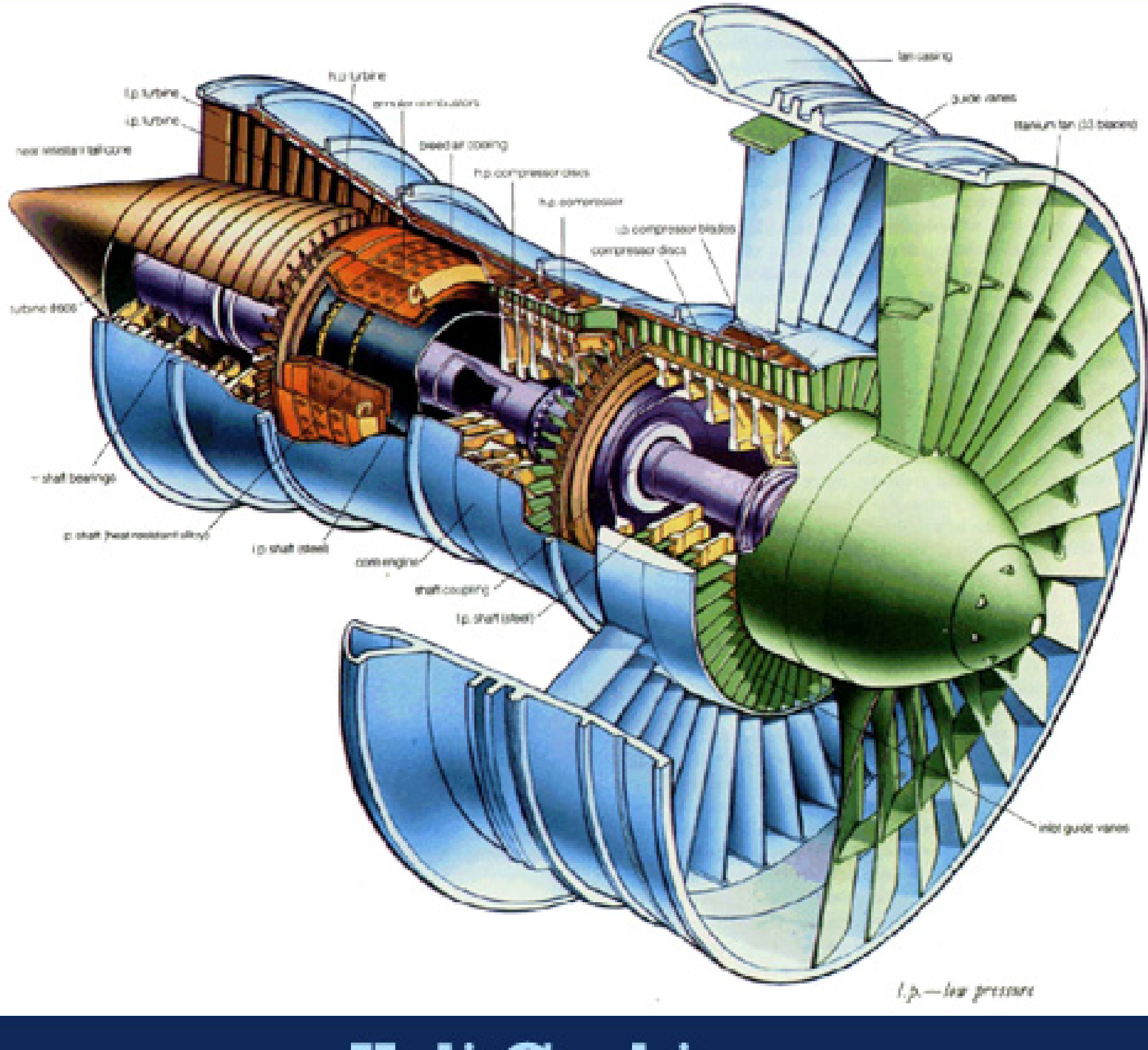
Handbook of Rotating Machines



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Chapter 1

Engine

An **engine** or **motor** is a machine designed to convert energy into useful mechanical motion.

Motors converting heat energy into motion are usually referred to as *engines*, which come in many types. A common type is a heat engine such as an internal combustion engine which typically burns a fuel with air and uses the hot gases for generating power. External combustion engines such as steam engines use heat to generate motion via a separate working fluid.

Another common type of motor is the electric motor. This takes electrical energy and generates mechanical motion via varying electromagnetic fields.

Other motors including pneumatic motors that are driven by compressed air, and motors can be driven by elastic energy, such as springs. Some motors are driven by non combustive chemical reactions.

Terminology

Originally an engine was a mechanical device that converted force into motion. Military devices such as catapults, trebuchets and battering rams are referred to as *siege engines*. The term "gin" as in cotton gin is recognised as a short form of the Old French word *engin*, in turn from the Latin *ingenium*, related to *ingenious*. Most devices used in the industrial revolution were referred to as engines, and this is where the steam engine gained its name.

In modern usage, the term is used to describe devices capable of performing mechanical work, as in the original steam engine. In most cases the work is produced by exerting a torque or linear force, which is used to operate other machinery which can generate electricity, pump water, or compress gas. In the context of propulsion systems, an air-breathing engine is one that uses atmospheric air to oxidise the fuel carried rather than supplying an independent oxidizer, as in a rocket.

In common usage, an *engine* burns or otherwise consumes fuel, and is differentiated from an electric machine (i.e., electric motor) that derives power without changing the composition of matter. A heat engine may also serve as a *prime mover*, a component that transforms the flow or changes in pressure of a fluid into mechanical energy. An automobile powered by an internal combustion engine may make use of various motors and pumps, but ultimately all such devices derive their power from the engine.

The term *motor* was originally used to distinguish the new internal combustion engine-powered vehicles from earlier vehicles powered by steam engines, such as the steam roller and motor roller, but may be used to refer to any engine.

History of engines

Antiquity

Simple machines, such as the club and oar (examples of the lever), are prehistoric. More complex engines using human power, animal power, water power, wind power and even steam power date back to antiquity. Human power was focused by the use of simple engines, such as the capstan, windlass or treadmill, and with ropes, pulleys, and block and tackle arrangements; this power was transmitted usually with the forces multiplied and the speed reduced. These were used in cranes and aboard ships in Ancient Greece, as well as in mines, water pumps and siege engines in Ancient Rome. The writers of those times, including Vitruvius, Frontinus and Pliny the Elder, treat these engines as commonplace, so their invention may be far more ancient. By the 1st century AD, various breeds of cattle and horses were used in mills, driving machines similar to those powered by humans in earlier times.

According to Strabo, a water powered mill was built in Kaberia of the kingdom of Mithridates during the 1st century BC. Use of water wheels in mills spread throughout the Roman Empire over the next few centuries. Some were quite complex, with aqueducts, dams, and sluices to maintain and channel the water, along with systems of gears, or toothed-wheels made of wood and metal to regulate the speed of rotation. In a poem by Ausonius in the 4th century AD, he mentions a stone-cutting saw powered by water. Hero of Alexandria is credited with many such wind and steam powered machines in the 1st century AD, including the Aeolipile, but it is not known if any of these were put to practical use.

Medieval

During the Muslim Agricultural Revolution from the 9th to 13th centuries, Muslim engineers developed numerous innovative industrial uses of hydropower, early industrial uses of tidal power, wind power, and fossil fuels such as petroleum, together with the earliest large factory complexes (*tiraz* in Arabic). The industrial uses of watermills in the

Islamic world date back to the 7th century, whereas horizontal-wheeled and vertical-wheeled water mills were both in widespread use since at least the 9th century. A variety of industrial mills were invented in the Islamic world, including fulling mills, hullers, steel mills, sugar refineries, and windmills. By the 11th century, every province throughout the Islamic world had these industrial mills in operation, from the Middle East and Central Asia to al-Andalus and North Africa.

Roman engineers invented water turbines in the 4th century AD, Muslim engineers employed gears in mills and water-raising machines, and pioneered the use of dams as a source of water power to provide additional power to watermills and water-raising machines. Such advances made it possible for many industrial tasks that were previously driven by manual labour to be mechanized and driven by machinery to some extent in the medieval Islamic world.

In 1206, al-Jazari employed a crank-connecting rod system for two of his water-raising machines. A similar steam turbine later appeared in Europe a century later, which eventually led to the steam engine and Industrial Revolution in 18th century Europe.

Industrial revolution

English inventor Sir Samuel Morland allegedly used gunpowder to drive water pumps in the 17th century. For more conventional, reciprocating internal combustion engines, the fundamental theory for two-stroke engines was established by Sadi Carnot, France, 1824, whilst the American Samuel Morey received a patent on April 1, 1826. Sir Dugald Clark (1854–1932) designed the first two-stroke engine in 1878 and patented it in England in 1881. Automotive engines have used a range of energy-conversion systems. These include electric, steam, solar, turbine, rotary, piston-type internal combustion engine.

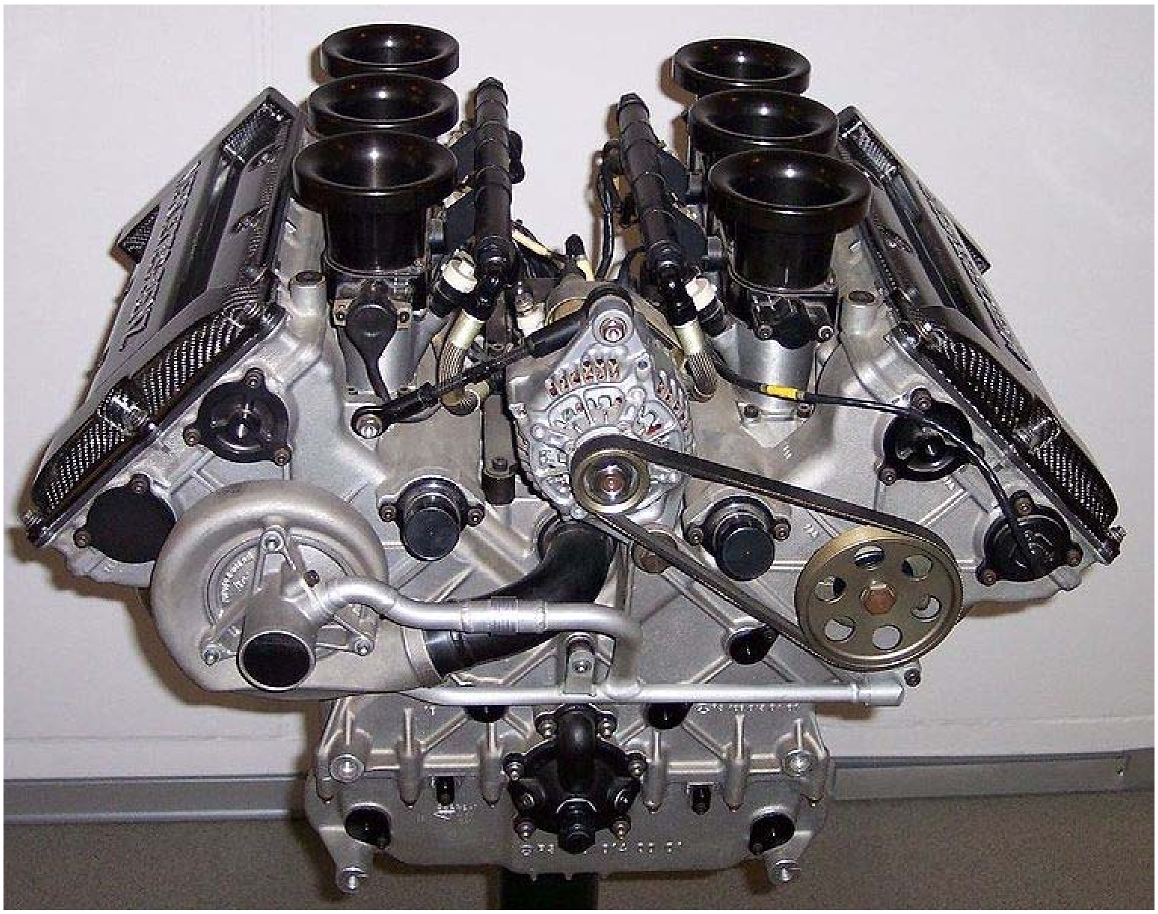
Karl Benz was one of the leaders in the development of new engines. In 1878 he began to work on new designs. He concentrated his efforts on creating a reliable gas two-stroke engine that was more powerful, based on Nikolaus Otto's design of the four-stroke engine. Karl Benz showed his real genius, however, through his successive inventions registered while designing what would become the production standard for his two-stroke engine. Benz was granted a patent for it in 1879.

The lightweight petrol internal combustion engine, operating on a four-stroke Otto cycle, has been the most successful for automobiles, while the more efficient diesel engine is used for trucks and buses.

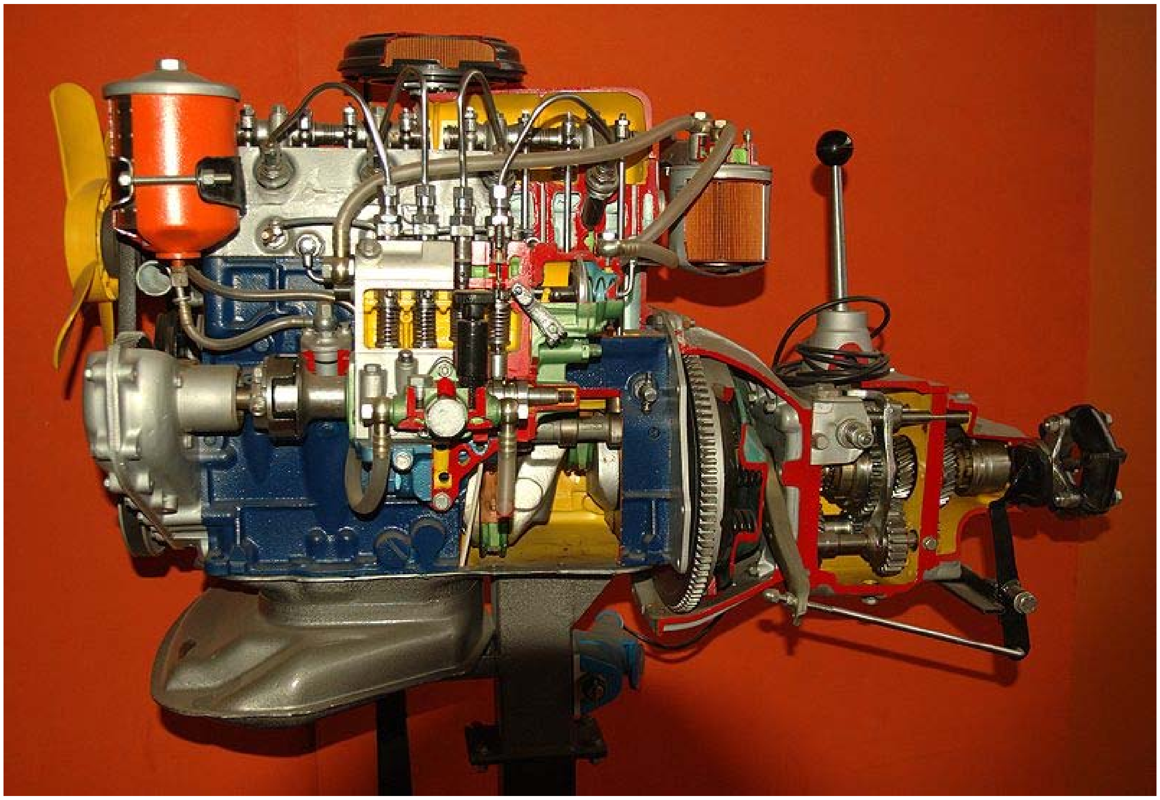
Horizontally opposed pistons

In 1896, Karl Benz was granted a patent for his design of the first engine with horizontally opposed pistons. Many BMW motorcycles use this engine type. His design created an engine in which the corresponding pistons move in horizontal cylinders and reach top dead center simultaneously, thus automatically balancing each other with respect to their individual momentums. Engines of this design are often referred to as flat engines because of their shape and lower profile. They must have an even number of cylinders and six, four or two cylinder flat engines have all been common. The most well-known engine of this type is probably the Volkswagen Beetle engine. Engines of this type continue to be a common design principle for high performance aero engines (for propeller driven aircraft) and, engines used by automobile producers such as Porsche and Subaru.

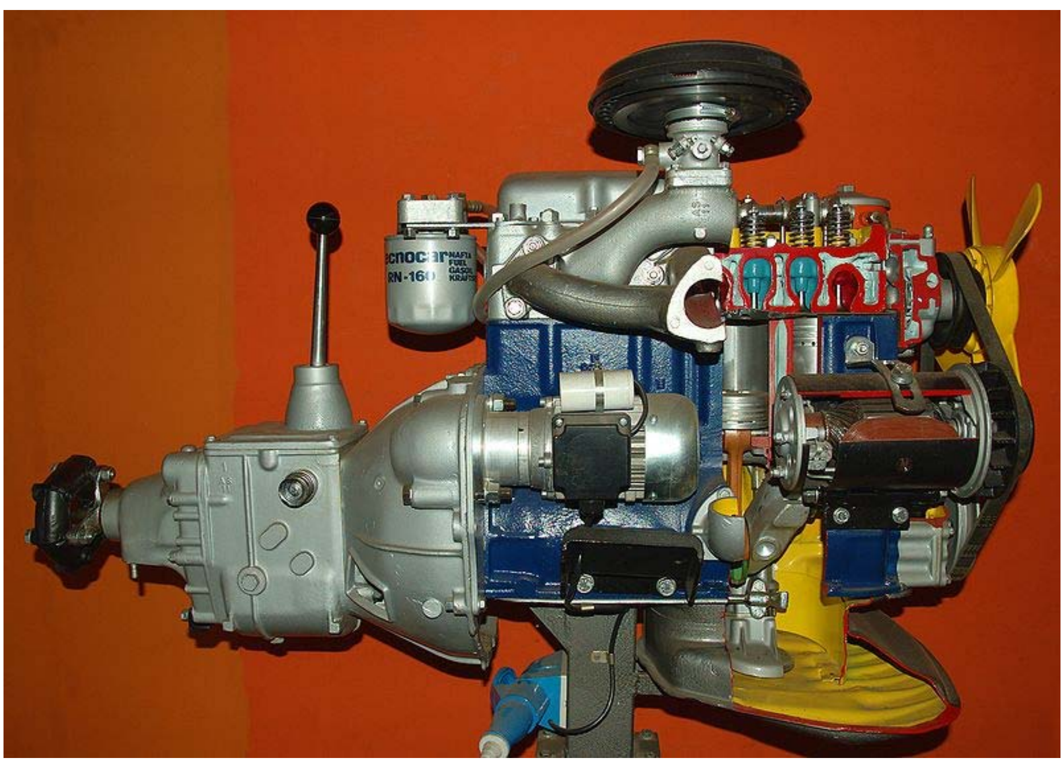
Advancement



Mercedes V6 engine in 1996



School model of engine



School model of an engine

Continuance of the use of the internal combustion engine for automobiles is partly due to the improvement of engine control systems (onboard computers providing engine management processes, and electronically controlled fuel injection). Forced air induction by turbocharging and supercharging have increased power outputs and engine efficiencies. Similar changes have been applied to smaller diesel engines giving them almost the same power characteristics as petrol engines. This is especially evident with the popularity of smaller diesel engine propelled cars in Europe. Larger diesel engines are still often used in trucks and heavy machinery. They do not burn as clean as gasoline engines, however they have far more torque. The internal combustion engine was originally selected for the automobile due to its flexibility over a wide range of speeds. Also, the power developed for a given weight engine was reasonable; it could be produced by economical mass-production methods; and it used a readily available, moderately priced fuel - petrol.

Increasing power

The first half of the 20th century saw a trend to increasing engine power, particularly in the American models. Design changes incorporated all known methods of raising engine capacity, including increasing the pressure in the cylinders to improve efficiency, increasing the size of the engine, and increasing the speed at which power is generated. The higher forces and pressures created by these changes created engine vibration and size problems that led to stiffer, more compact engines with V and opposed cylinder layouts replacing longer straight-line arrangements.

Combustion efficiency

The design principles favoured in Europe, because of economic and other restraints such as smaller and twistier roads, leant toward smaller cars and corresponding to the design principles that concentrated on increasing the combustion efficiency of smaller engines. This produced more economical engines with earlier four-cylinder designs rated at 40 horsepower (30 kW) and six-cylinder designs rated as low as 80 horsepower (60 kW), compared with the large volume V-8 American engines with power ratings in the range from 250 to 350 hp (190 to 260 kW).

Engine configuration

Earlier automobile engine development produced a much larger range of engines than is in common use today. Engines have ranged from 1 to 16 cylinder designs with corresponding differences in overall size, weight, piston displacement, and cylinder bores. Four cylinders and power ratings from 19 to 120 hp (14 to 90 kW) were followed in a majority of the models. Several three-cylinder, two-stroke-cycle models were built while most engines had straight or in-line cylinders. There were several V-type models and horizontally opposed two- and four-cylinder makes too. Overhead camshafts were frequently employed. The smaller engines were commonly air-cooled and located at the rear of the vehicle; compression ratios were relatively low. The 1970s and '80s saw an increased interest in improved fuel economy which brought in a return to smaller V-6 and four-cylinder layouts, with as many as five valves per cylinder to improve efficiency. The

Bugatti Veyron 16.4 operates with a W16 engine meaning that two V8 cylinder layouts are positioned next to each other to create the W shape.

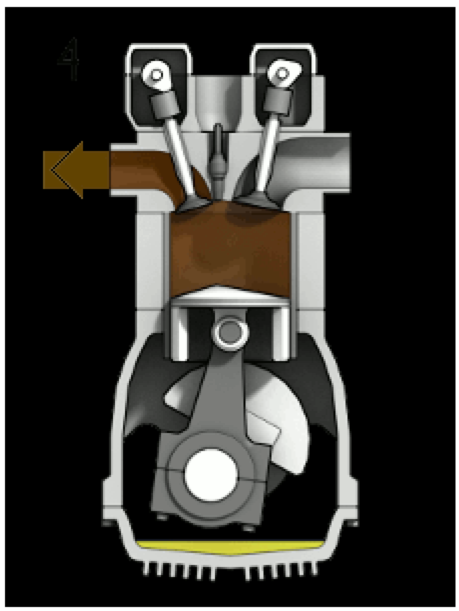
The largest internal combustion engine ever built is the Wärtsilä-Sulzer RTA96-C, a 14-cylinder, 2-stroke turbocharged diesel engine that was designed to power the Emma Maersk, the largest container ship in the world. This engine weighs 2300 tons, and when running at 102 RPM produces 109,000 bhp (80,080 kW) consuming some 13.7 tons of fuel each hour.

Heat engine

Combustion engine

Combustion engines are heat engines driven by the heat of a combustion process.

Internal combustion engine



the four stages of the 4-stroke combustion engine cycle:
1. Induction *(Fuel enters)*
2. Compression
3. Ignition *(Fuel is burnt)*
4. Emission *(Exhaust out)*

The **internal combustion engine** is an engine in which the combustion of a fuel (generally, fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber. In an internal combustion engine the expansion of the high temperature and high pressure gases, which are produced by the combustion, directly applies force to components of the engine, such as the pistons or turbine blades or a nozzle, and by moving it over a distance, generates useful mechanical energy.

External combustion engine

An **external combustion engine** (EC engine) is a heat engine where an internal working fluid is heated by combustion of an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine produces motion and usable work. The fluid is then cooled, compressed and reused (closed cycle), or (less commonly) dumped, and cool fluid pulled in (open cycle air engine).

"Combustion" refers to burning fuel with an oxidizer, to supply the heat. Engines of similar (or even identical) configuration and operation may use a supply of heat from other sources such as nuclear, solar, geothermal or exothermic reactions not involving combustion; but are not then strictly classed as external combustion engines, but as external thermal engines.

The working fluid can be a gas as in a Stirling engine, or steam as in a steam engine or an organic liquid such as n-pentane in an Organic Rankine Cycle. The fluid can be of any composition; gas is by far the most common, although even single-phase liquid is sometimes used. In the case of the steam engine, the fluid changes phases between liquid and gas...

Gas turbine

A gas turbine is internal combustion is the sense that the combustion takes place in the working fluid, but external combustion in the sense that the combustion is not fully closed in and is outside the actual moving turbine section. Traditionally, "internal combustion" usually excludes gas turbines, jets and rockets.

Air-breathing combustion engines

Air-breathing engines are combustion engines that use the oxygen in atmospheric air to oxidise ('burn') the fuel carried, rather than carrying an oxidiser, as in a rocket. Theoretically, this should result in a better specific impulse than for rocket engines.

A continuous stream of air flows through the Air-breathing engine. This air is compressed, mixed with fuel, ignited and expelled as the exhaust gas. Thrust produced by a typical air-breathing engine is about eight times greater than its weight. The maximum velocity of Air-breathing engines is limited to 1–3 km/s due to extreme temperature and dissociation of the exhaust gas; however, the maximum velocity of a hydrogen-breathing engine of the same design is about 4 times higher.

Examples

Typical air-breathing engines include:

- Reciprocating engine

- Steam engine
- Gas turbine

duct jet engine
Turbo-propeller engine

- IRIS engine
- Pulse detonation engine
- Pulse jet
- Ramjet
- Scramjet
- Liquid air cycle engine/Reaction Engines SABRE

Environmental effects

Operation of engines typically has a negative impact upon air quality and ambient sound levels. There has been a growing emphasis on the pollution producing features of automotive power systems. This has created new interest in alternate power sources and internal-combustion engine refinements. Although a few limited-production battery-powered electric vehicles have appeared, they have not proved to be competitive owing to costs and operating characteristics. In the 21st century the diesel engine has been increasing in popularity with automobile owners. However, the gasoline engine, with its new emission-control devices to improve emission performance, has not yet been significantly challenged.

Air quality

Exhaust from a spark ignition engine consists of the following: nitrogen 70 to 75% (by volume), water vapor 10 to 12%, carbon dioxide 10 to 13.5%, hydrogen 0.5 to 2%, oxygen 0.2 to 2%, carbon monoxide: 0.1 to 6%, unburnt hydrocarbons and partial oxidation products (e.g. aldehydes) 0.5 to 1%, nitrogen monoxide 0.01 to 0.4%, nitrous oxide <100 ppm, sulfur dioxide 15 to 60 ppm, traces of other compounds such as fuel additives and lubricants, also halogen and metallic compounds, and other particles. Carbon monoxide is highly toxic, and can cause carbon monoxide poisoning, so it is important to avoid any build-up of the gas in a confined space. Catalytic converters can reduce toxic emissions, but not completely eliminate them. Also, resulting greenhouse gas emissions, chiefly carbon dioxide, from the widespread use of engines in the modern industrialized world is contributing to the global greenhouse effect – a primary concern regarding global warming.

Non combustive heat engines

Some engines convert heat from non combustive processes into mechanical work, for example a nuclear power plant uses the heat from the nuclear reaction to produce steam and drive a steam engine, or a gas turbine in a rocket engine may be driven by decomposing hydrogen peroxide. Apart from the different energy source, the engine is often engineered much the same as an internal or external combustion engine.

Non thermal chemically powered motor

Non thermal motors usually are powered by a chemical reaction, but are not heat engines. Examples include:

- Molecular motor - motors found in living things
- Synthetic molecular motor

Electric motor

An **electric motor** uses electrical energy to produce mechanical energy, usually through the interaction of magnetic fields and current-carrying conductors. The reverse process, producing electrical energy from mechanical energy, is accomplished by a generator or dynamo. Traction motors used on vehicles often perform both tasks. Electric motors can be run as generators and vice versa, although this is not always practical. Electric motors are ubiquitous, being found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives. They may be powered by direct current (for example a battery powered portable device or motor vehicle), or by alternating current from a central electrical distribution grid. The smallest motors may be found in electric wristwatches. Medium-size motors of highly standardized dimensions and characteristics provide convenient mechanical power for industrial uses. The very largest electric motors are used for propulsion of large ships, and for such purposes as pipeline compressors, with ratings in the thousands of kilowatts. Electric motors may be classified by the source of electric power, by their internal construction, and by their application.

The physical principle of production of mechanical force by the interactions of an electric current and a magnetic field was known as early as 1821. Electric motors of increasing efficiency were constructed throughout the 19th century, but commercial exploitation of electric motors on a large scale required efficient electrical generators and electrical distribution networks.

By convention, *electric engine* refers to a railroad electric locomotive, rather than an electric motor.

Physically powered engine

Some engines are powered by potential energy, for example some clocks have a weight that falls under gravity. Other forms of potential energy include compressed gases (such as pneumatic motors), springs and elastic bands.

Historic military siege engines included large catapults, trebuchets, and (to some extent) battering rams were powered by potential energy.

Pneumatic motor

A **pneumatic motor** is a machine which converts potential energy in the form of compressed air into mechanical work. Pneumatic motors generally convert the compressed air to mechanical work though either linear or rotary motion. Linear motion can come from either a diaphragm or piston actuator, while rotary motion is supplied by either a vane type air motor or piston air motor. Pneumatic motors have found widespread success in the hand-held tool industry and continual attempts are being made to expand their use to the transportation industry. However, pneumatic motors must overcome efficiency deficiencies before being seen as a viable option in the transportation industry.

Hydraulic engine

A **hydraulic engine** one that derives its power from a pressurized fluid. This type of engine can be used to move heavy loads or produce motion.

Sound levels

In the case of sound levels, engine operation is of greatest impact with respect to mobile sources such as automobiles and trucks. Engine noise is a particularly large component of mobile source noise for vehicles operating at lower speeds, where aerodynamic and tyre noise is less significant. Petrol and diesel engines are fitted with mufflers (silencers) to reduce noise.

Engine efficiency

Depending on the type of engine employed, different rates of efficiency are attained.

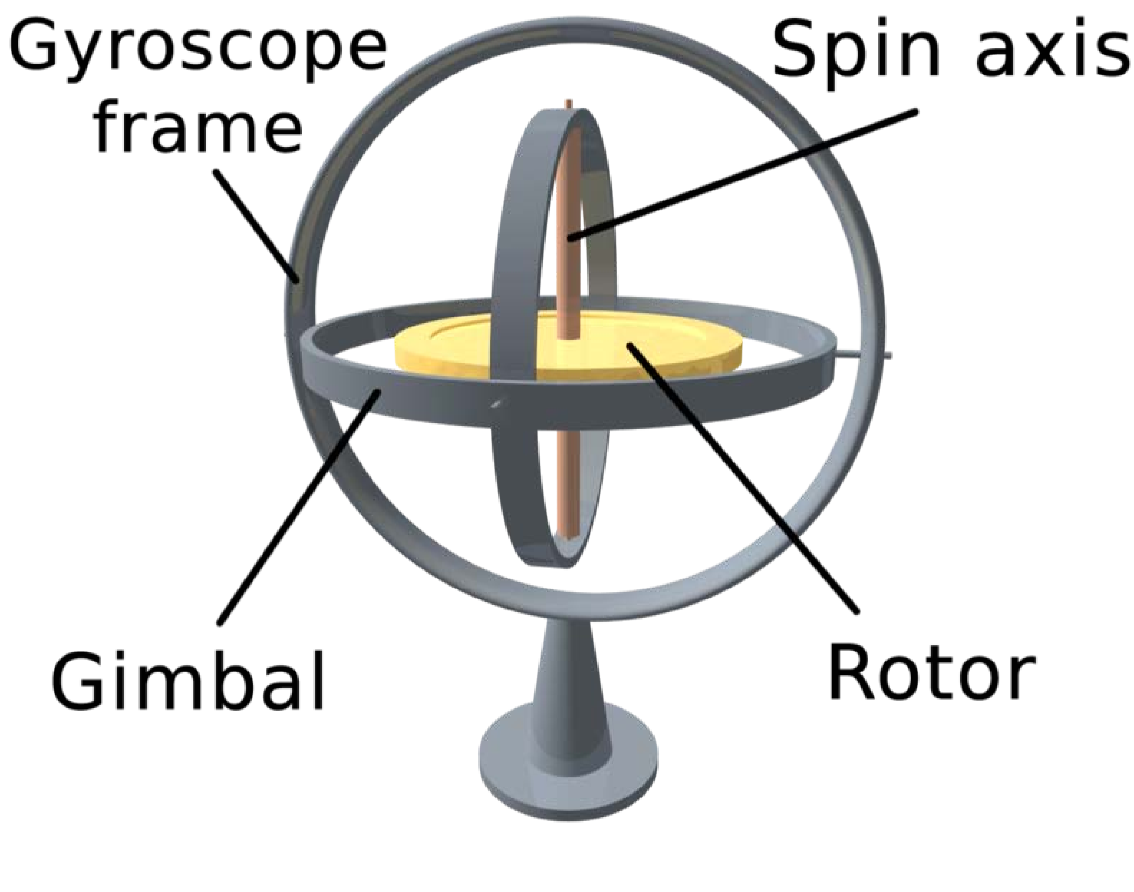
Engines by use

Particularly notable kinds of engines include:

- Aircraft engine
- Automobile engine
- model engine
- Motorcycle engine
- Marine propulsion engines such as Outboard motor
- Railway locomotive engine
- Spacecraft propulsion engines such as Rocket engine
- Traction engine

Chapter 2

Gyroscope



A gyroscope

A **gyroscope** is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum. A mechanical gyroscope is essentially a spinning wheel or disk whose axle is free to take any orientation. This orientation changes much less in response to a given external torque than it would without the large angular momentum associated with the gyroscope's high rate of spin. Since external torque is minimized by mounting the device in gimbals, its orientation remains nearly fixed, regardless of any motion of the platform on which it is mounted.

Gyroscopes based on other operating principles also exist, such as the electronic, microchip-packaged MEMS gyroscope devices found in consumer electronic devices, solid state ring lasers, fibre optic gyroscopes and the extremely sensitive quantum gyroscope.

Applications of gyroscopes include navigation (INS) when magnetic compasses do not work (as in the Hubble telescope) or are not precise enough (as in ICBMs) or for the stabilization of flying vehicles like radio-controlled helicopters or UAVs. Due to their high precision, gyroscopes are also used to maintain direction in tunnel mining.

Description and diagram

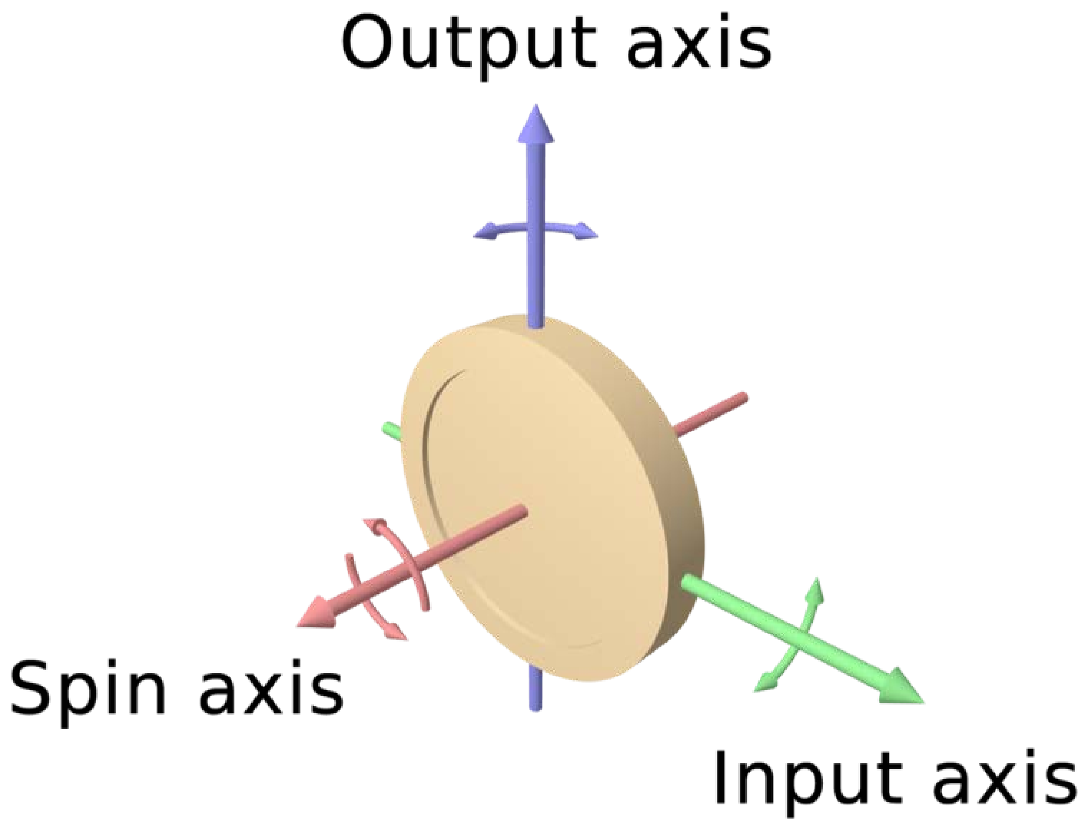


Diagram of a gyro wheel. Reaction arrows about the output axis (blue) correspond to forces applied about the input axis (green), and vice versa.

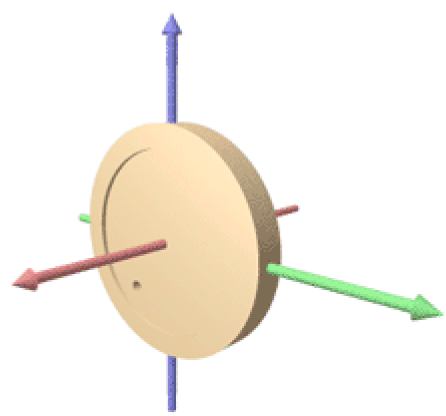
Within mechanical systems or devices, a conventional *gyroscope* is a mechanism comprising a rotor journalled to spin about one axis, the journals of the rotor being mounted in an inner gimbal or ring, the inner gimbal is journalled for oscillation in an outer gimbal which is journalled in another gimbal for a total of three gimbals.

The **outer gimbal** or ring which is the gyroscope frame is mounted so as to pivot about an axis in its own plane determined by the support. This outer gimbal possesses one degree of rotational freedom and its axis possesses none. The next **inner gimbal** is mounted in the gyroscope frame (outer gimbal) so as to pivot about an axis in its own plane that is always perpendicular to the pivotal axis of the gyroscope frame (outer gimbal). This inner gimbal has two degrees of rotational freedom. Similarly, next **innermost gimbal** is attached to the inner gimbal which has three degrees of rotational freedom and its axis possesses two.

The axle of the spinning wheel defines the spin axis. The rotor is journaled to spin about an axis which is always perpendicular to the axis of the innermost gimbal. So, the rotor possesses four degrees of rotational freedom and its axis possesses three. The wheel responds to a force applied about the input axis by a reaction force about the output axis.

The behaviour of a gyroscope can be most easily appreciated by consideration of the front wheel of a bicycle. If the wheel is leaned away from the vertical so that the top of the wheel moves to the left, the forward rim of the wheel also turns to the left. In other words, rotation on one axis of the turning wheel produces rotation of the third axis.

A **gyroscope flywheel** will roll or resist about the output axis depending upon whether the output gimbals are of a free- or fixed- configuration. Examples of some free-output-gimbal devices would be the attitude reference gyroscopes used to sense or measure the pitch, roll and yaw attitude angles in a spacecraft or aircraft.



Gyro wheel in action

The centre of gravity of the rotor can be in a fixed position. The rotor simultaneously spins about one axis and is capable of oscillating about the two other axes, and thus, except for its inherent resistance due to rotor spin, it is free to turn in any direction about the fixed point. Some gyroscopes have mechanical equivalents substituted for one or more of the elements, e.g., the spinning rotor may be suspended in a fluid, instead of being pivotally mounted in gimbals. A control moment gyroscope (CMG) is an example of a fixed-output-gimbal device that is used on spacecraft to hold or maintain a desired attitude angle or pointing direction using the gyroscopic resistance force.

In some special cases, the outer gimbal (or its equivalent) may be omitted so that the rotor has only two degrees of freedom. In other cases, the centre of gravity of the rotor may be offset from the axis of oscillation and thus the centre of gravity of the rotor and the centre of suspension of the rotor may not coincide.

History

Gyroscope invented by Léon Foucault in 1852. Replica built by Dumoulin-Froment for the Exposition universelle in 1867. National Conservatory of Arts and Crafts museum, Paris.

The earliest known gyroscope-like instrument was made by German Johann Bohnenberger, who first wrote about it in 1817. At first he called it the "Machine". Bohnenberger's machine was based on a rotating massive sphere. In 1832, American Walter R. Johnson developed a similar device that was based on a rotating disk. The French mathematician Pierre-Simon Laplace, working at the École Polytechnique in Paris, recommended the machine for use as a teaching aid, and thus it came to the attention of Léon Foucault. In 1852, Foucault used it in an experiment involving the rotation of the Earth. It was Foucault who gave the device its modern name, in an experiment to see the Earth's rotation (Greek *gyros*, circle or rotation), which was visible in the 8 to 10 minutes before friction slowed the spinning rotor.

In the 1860s, the advent of electric motors made it possible for a gyroscope to spin indefinitely; this lead to the first prototype gyrocompasses. The first functional marine gyrocompass was patented in 1907 by German inventor Hermann Anschütz-Kaempfe. The American Elmer Sperry followed with his own design later that year, and other nations soon realized the military importance of the invention—in an age in which naval prowess was the most significant measure of military power—and created their own gyroscope industries. The Sperry Gyroscope Company quickly expanded to provide aircraft and naval stabilizers as well, and other gyroscope developers followed suit.

In 1917, the Chandler Company of Indianapolis, Indiana, created the "Chandler gyroscope", a toy gyroscope with a pull string and pedestal. Chandler continued to produce the toy until the company was purchased by TEDCO inc. in 1982. The chandler toy is still produced by TEDCO today.

In the first several decades of the 20th century, other inventors attempted (unsuccessfully) to use gyroscopes as the basis for early black box navigational systems by creating a stable platform from which accurate acceleration measurements could be performed (in order to bypass the need for star sightings to calculate position). Similar principles were later employed in the development of inertial guidance systems for ballistic missiles.

During World War Two, the gyroscope became the prime component for aircraft and anti-aircraft gun sights.

Properties

A gyroscope in operation with freedom in all three axes. The rotor will maintain its spin axis direction regardless of the orientation of the outer frame.

A gyroscope exhibits a number of behaviours including precession and nutation. Gyroscopes can be used to construct gyrocompasses which complement or replace magnetic compasses (in ships, aircraft and spacecraft, vehicles in general), to assist in stability (Hubble Space Telescope, bicycles, motorcycles, and ships) or be used as part of an inertial guidance system. Gyroscopic effects are used in tops, boomerangs, yo-yos, and Powerballs. Many other rotating devices, such as flywheels, behave gyroscopically although the gyroscopic effect is not being used.

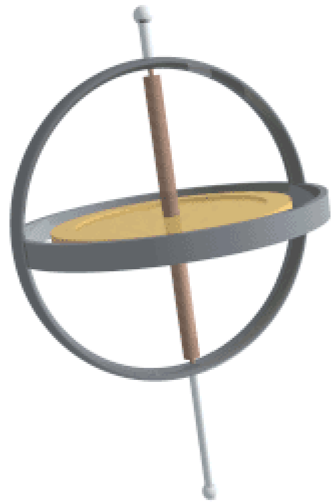
The fundamental equation describing the behavior of the gyroscope is:

$$\boldsymbol{\tau} = \frac{d\mathbf{L}}{dt} = \frac{d(I\boldsymbol{\omega})}{dt} = I\boldsymbol{\alpha}$$

where the vectors $\boldsymbol{\tau}$ and $\mathbf{L}$ are, respectively, the torque on the gyroscope and its angular momentum, the scalar I is its moment of inertia, the vector $\boldsymbol{\omega}$ is its angular velocity, and the vector $\boldsymbol{\alpha}$ is its angular acceleration.

It follows from this that a torque $\boldsymbol{\tau}$ applied perpendicular to the axis of rotation, and therefore perpendicular to $\mathbf{L}$, results in a rotation about an axis perpendicular to both $\boldsymbol{\tau}$ and $\mathbf{L}$. This motion is called *precession*. The angular velocity of precession $\boldsymbol{\Omega}_{\mathrm{P}}$ is given by the cross product:

$$\boldsymbol{\tau} = \boldsymbol{\Omega}_{\mathrm{P}} \times \mathbf{L}.$$



Precession on a gyroscope

Precession can be demonstrated by placing a spinning gyroscope with its axis horizontal and supported loosely (frictionless toward precession) at one end. Instead of falling, as might be expected, the gyroscope appears to defy gravity by remaining with its axis horizontal, when the other end of the axis is left unsupported and the free end of the axis slowly describes a circle in a horizontal plane, the resulting precession turning. This effect is explained by the above equations. The torque on the gyroscope is supplied by a couple of forces: gravity acting downwards on the device's centre of mass, and an equal force acting upwards to support one end of the device. The rotation resulting from this torque is not downwards, as might be intuitively expected, causing the device to fall, but perpendicular to both the gravitational torque (horizontal and perpendicular to the axis of rotation) and the axis of rotation (horizontal and outwards from the point of support), i.e. about a vertical axis, causing the device to rotate slowly about the supporting point.

Under a constant torque of magnitude τ, the gyroscope's speed of precession $\mathit{\Omega}_\mathrm{P}$ is inversely proportional to L, the magnitude of its angular momentum:

$$\tau = \mathit{\Omega}_\mathrm{P} L \sin\theta,$$

where θ is the angle between the vectors $\mathbf{\Omega}_\mathrm{P}$ and $\mathbf{L}$. Thus if the gyroscope's spin slows down (for example, due to friction), its angular momentum decreases and so the rate of precession increases. This continues until the device is unable to rotate fast enough to support its own weight, when it stops precessing and falls off its support, mostly because friction against precession cause another precession that goes to cause the fall.

By convention, these three vectors, torque, spin, and precession, are all oriented with respect to each other according to the right-hand rule.

To easily ascertain the direction of gyro effect, simply remember that a rolling wheel tends, when it leans to the side, to turn in the direction of the lean.

Variations

Gyrostat

A **gyrostat** is a variant of the gyroscope. It consists of a massive flywheel concealed in a solid casing. Its behaviour on a table, or with various modes of suspension or support, serves to illustrate the curious reversal of the ordinary laws of static equilibrium due to the gyrostatic behaviour of the interior invisible flywheel when rotated rapidly. The first gyrostat was designed by Lord Kelvin to illustrate the more complicated state of motion of a spinning body when free to wander about on a horizontal plane, like a top spun on the pavement, or a hoop or bicycle on the road.

MEMS

A MEMS gyroscope takes the idea of the Foucault pendulum and uses a vibrating element, known as a MEMS (Micro Electro-Mechanical System). The MEMS-based gyro was initially made practical and producible by Systron Donner Inertial (SDI). Today, SDI is a large manufacturer of MEMS gyroscopes.

FOG

A fiber optic gyroscope (FOG) is a gyroscope that uses the interference of light to detect mechanical rotation. The sensor is a coil of as much as 5 km of optical fiber. The development of low loss single mode optical fiber in the early 1970s for the telecommunications industry enabled the development of Sagnac effect fiber optic gyros.

VSG or CVG

A vibrating structure gyroscope (VSG), also called a **coriolis vibratory gyroscope** (CVG), uses a resonator made of different metallic alloys. It takes a position between the low accuracy, low cost MEMS gyroscope and the higher accuracy and higher cost fiber optic gyroscope (FOG). Accuracy parameters are increased by using low intrinsic damping materials, resonator vacuumization, and digital electronics to reduce temperature dependent drift and instability of control signals.

High-Q Wine-Glass Resonators for precise sensors like HRG or CRG are based on Bryan's "wave inertia effect". They are made from high-purity quartz glass or from single-crystalline sapphire.

DTG

A dynamically tuned gyroscope (DTG) is a rotor suspended by a universal joint with flexure pivots. The flexure spring stiffness is independent of spin rate. However, the dynamic inertia (from the gyroscopic reaction effect) from the gimbal provides negative spring stiffness proportional to the square of the spin speed (Howe and Savet, 1964; Lawrence, 1998). Therefore, at a particular speed, called the tuning speed, the two moments cancel each other, freeing the rotor from torque, a necessary condition for an ideal gyroscope.

London moment

A London moment gyroscope relies on the quantum-mechanical phenomenon whereby a

spinning superconductor generates a magnetic field whose axis lines up exactly with the spin axis of the gyroscopic rotor. A magnetometer determines the orientation of the generated field, which is interpolated to determine the axis of rotation. Gyroscopes of this type can be extremely accurate and stable, for example those used in the Gravity Probe B experiment measured changes in gyroscope spin axis orientation to better than 0.5 milliarcseconds (1.4×10^{-7} degrees) over a one-year period. This is equivalent to an angular separation the width of a human hair viewed from 32 kilometers (20 miles) away.

The GP-B gyro consists of a nearly-perfect spherical rotating mass made of fused quartz which provides a dielectric support for a thin layer of niobium superconducting material. To eliminate friction found in conventional mechanical bearings, the rotor assembly is suspended by six electromagnets that form a magnetic bearing. After the initial spin-up by a jet of helium brings the rotor to 4,000 RPM, the polished gyroscope housing is evacuated to a ultra-high vacuum to further reduce drag on the rotor. Provided the suspension electronics remain powered, the extreme rotational symmetry, lack of friction, and low drag will allow the angular momentum of the rotor to keep it spinning for about 15,000 years.

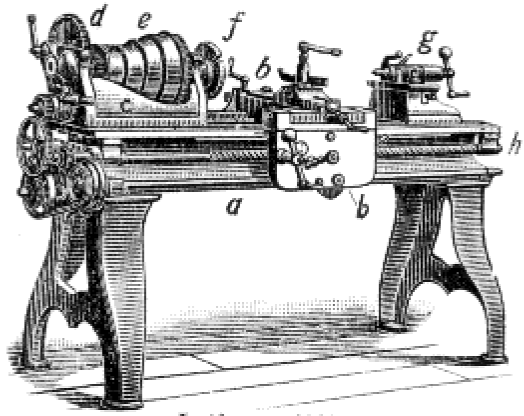
A sensitive DC SQUID magnetometer able to discriminate changes as small as one quantum, or about 2×10^{-15} Wb, is used to monitor the gyroscope. A precesses, or tilt, in the orientation of the rotor causes the London moment magnetic field to shift relative to the housing. The moving field passes through a superconducting pickup loop fixed to the housing, inducing a small electric current. The current produces a voltage across a shunt resistance, which is resolved to spherical coordinates by a microprocessor. The system is designed to minimize Lorentz torque on the rotor.

Modern uses

In addition to being used in compasses, aircraft, computer pointing devices, etc., gyroscopes have been introduced into consumer electronics. Since the gyroscope allows the calculation of orientation and rotation, designers have incorporated them into modern technology. The integration of the gyroscope has allowed for more accurate recognition of movement within a 3D space than the previous lone accelerometer within a number of smartphones. Scott Steinberg, known for his critiques on newly released technology, says that the new addition of the gyroscope in the iPhone 4 may "completely redefine the way we interact with downloadable apps".

Chapter 3

Lathe



Lathe, p. 1218.

A metalworking lathe from 1911 showing component parts.
a = bed, b = carriage (with cross-slide and toolpost), c = headstock, d = back gear (other geartrain nearby below drives leadscrew), e = cone pulley for belt drive from an external power source, f = faceplate mounted on spindle, g = tailstock. h = leadscrew.

A **lathe** is a machine tool which rotates the workpiece on its axis to perform various operations such as cutting, sanding, knurling, drilling, or deformation with tools that are applied to the workpiece to create an object which has symmetry about an axis of rotation.

Lathes are used in woodturning, metalworking, metal spinning, and glassworking. Lathes can be used to shape pottery, the best-known design being the potter's wheel. Most suitably equipped metalworking lathes can also be used to produce most solids of revolution, plane surfaces and screw threads or helices. Ornamental lathes can produce three-dimensional solids of incredible complexity. The material can be held in place by either one or two *centers*, at least one of which can be moved horizontally to accommodate varying material lengths. Other workholding methods include clamping the work about the axis of rotation using a chuck or collet, or to a faceplate, using clamps or dogs.

Examples of objects that can be produced on a lathe include candlestick holders, cue sticks, table legs, bowls, baseball bats, musical instruments (especially woodwind instruments), crankshafts and camshafts.

History

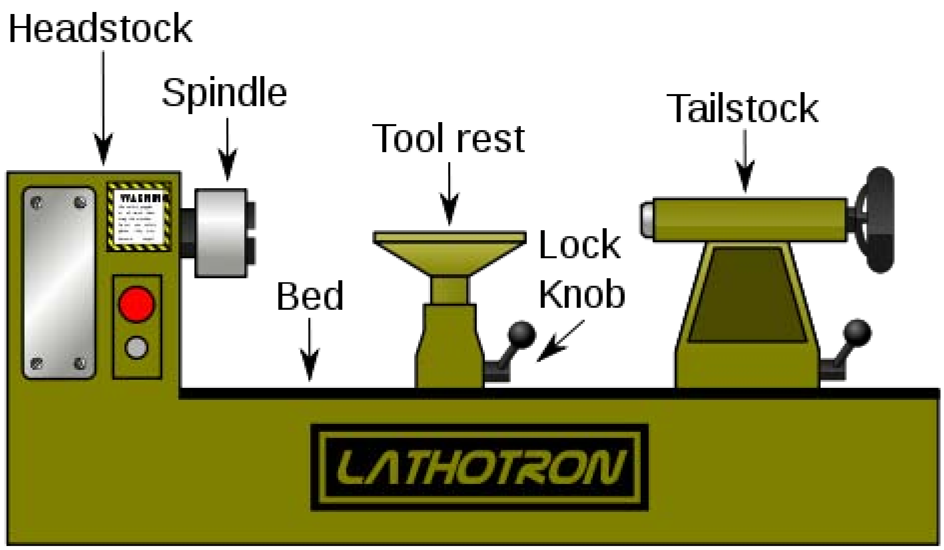
The lathe is an ancient tool, dating at least to ancient Egypt and known and used in Assyria, ancient Greece, and the Roman and Byzantine Empires.

The origin of turning dates to around 1300 BC when the Egyptians first developed a two-person lathe. One person would turn the wood work piece with a rope while the other used a sharp tool to cut shapes in the wood. The Romans improved the Egyptian design with the addition of a turning bow. Early bow lathes were also developed and used in Germany, France and Britain. In the Middle Ages a pedal replaced hand-operated turning, freeing both the craftsman's hands to hold the woodturning tools. The pedal was usually connected to a pole, often a straight-grained sapling. The system today is called the "spring pole" lathe. Spring pole lathes were in common use into the early 20th century. A two-person lathe, called a "great lathe", allowed a piece to turn continuously (like today's power lathes). A master would cut the wood while an apprentice turned the crank.

During the Industrial Revolution, mechanized power generated by water wheels or steam engines was transmitted to the lathe via line shafting, allowing faster and easier work. The design of lathes diverged between woodworking and metalworking to a greater extent than in previous centuries. Metalworking lathes evolved into heavier machines with thicker, more rigid parts. The application of leadscrews, slide rests, and gearing produced commercially practical screw-cutting lathes. Between the late 19th and mid-20th centuries, individual electric motors at each lathe replaced line shafting as the power source. Beginning in the 1950s, servomechanisms were applied to the control of lathes and other machine tools via numerical control (NC), which often was coupled with computers to yield computerized numerical control (CNC). Today manually controlled and CNC lathes coexist in the manufacturing industries.

Description

Parts



Parts of a wood lathe

A lathe may or may not have a **stand** (or **legs**), which sits on the floor and elevates the lathe bed to a working height. Some lathes are small and sit on a **workbench** or **table**, and do not have a stand.

Almost all lathes have a **bed**, which is (almost always) a horizontal beam (although some CNC lathes have a vertical beam for a bed to ensure that swarf, or chips, falls free of the bed). A notable exception is the Hegner VB36 Master Bowlturner, a woodturning lathe designed for turning large bowls, which in its basic configuration is little more than a very large floor-standing headstock.

At one end of the bed (almost always the left, as the operator faces the lathe) is a **headstock**. The headstock contains high-precision spinning bearings. Rotating within the bearings is a horizontal axle, with an axis parallel to the bed, called the **spindle**. Spindles are often hollow, and have exterior threads and/or an interior Morse taper on the "inboard" (i.e., facing to the right / towards the bed) by which workholding accessories may be mounted to the spindle. Spindles may also have exterior threads and/or an interior taper at their "outboard" (i.e., facing away from the bed) end, and/or may have a handwheel or other accessory mechanism on their outboard end. Spindles are powered, and impart motion to the workpiece.

The spindle is driven, either by foot power from a treadle and flywheel or by a belt or gear drive to a **power source**. In most modern lathes this power source is an integral electric motor, often either in the headstock, to the left of the headstock, or beneath the headstock, concealed in the stand.

In addition to the spindle and its bearings, the headstock often contains parts to convert the motor speed into various spindle speeds. Various types of **speed-changing mechanism** achieve this, from a cone pulley or step pulley, to a cone pulley with back gear (which is essentially a low range, similar in net effect to the two-speed rear of a truck), to an entire gear train similar to that of a manual-shift auto transmission. Some motors have electronic rheostat-type speed controls, which obviates cone pulleys or gears.

The counterpoint to the headstock is the **tailstock**, sometimes referred to as the loose head, as it can be positioned at any convenient point on the bed, by undoing a locking nut, sliding it to the required area, and then relocking it. The tailstock contains a barrel which does not rotate, but can slide in and out parallel to the axis of the bed, and directly in line with the headstock spindle. The barrel is hollow, and usually contains a taper to facilitate the gripping of various type of tooling. Its most common uses are to hold a hardened steel centre, which is used to support long thin shafts while turning, or to hold drill bits for drilling axial holes in the work piece. Many other uses are possible.

Metalworking lathes have a **carriage** (comprising a **saddle** and **apron**) topped with a **cross-slide**, which is a flat piece that sits crosswise on the bed, and can be cranked at right angles to the bed. Sitting atop the cross slide is usually another slide called a **compound rest**, which provides 2 additional axes of motion, rotary and linear. Atop that sits a **toolpost**, which holds a **cutting tool** which removes material from the workpiece. There may or may not be a **leadscrew**, which moves the cross-slide along the bed.

Woodturning and metal spinning lathes do not have cross-slides, but rather have **banjos**, which are flat pieces that sit crosswise on the bed. The position of a banjo can be adjusted by hand; no gearing is involved. Ascending vertically from the banjo is a toolpost, at the top of which is a horizontal **toolrest**. In woodturning, hand tools are braced against the tool rest and levered into the workpiece. In metal spinning, the further pin ascends vertically from the tool rest, and serves as a fulcrum against which tools may be levered into the workpiece.

Accessories

A steady rest

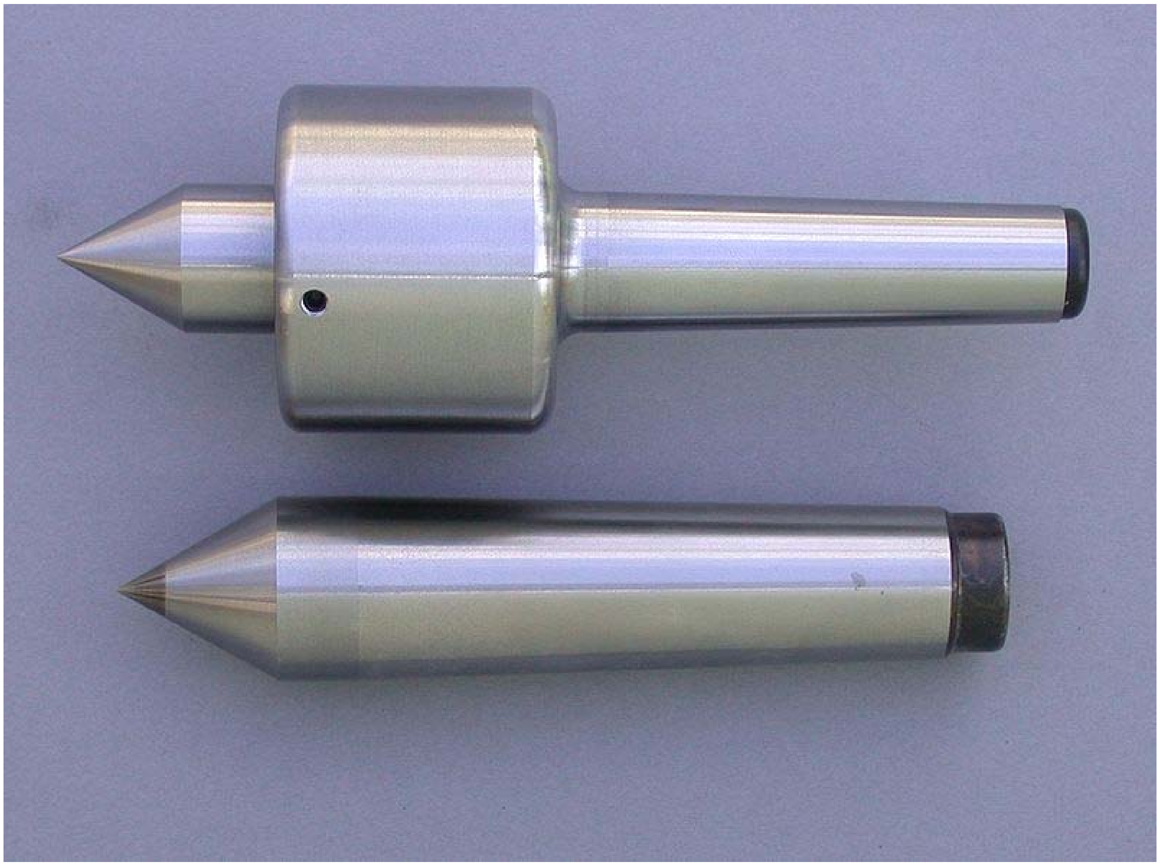
Unless a workpiece has a taper machined onto it which perfectly matches the internal taper in the spindle, or has threads which perfectly match the external threads on the spindle (two conditions which rarely exist), an accessory must be used to mount a workpiece to the spindle.

A workpiece may be bolted or screwed to a faceplate, a large, flat disk that mounts to the spindle. In the alternative, faceplate dogs may be used to secure the work to the faceplate.

A workpiece may be mounted on a mandrel, or circular work clamped in a three- or four-jaw chuck. For irregular shaped workpieces it is usual to use a four jaw (independent moving jaws) chuck. These holding devices mount directly to the Lathe headstock spindle.

In precision work, and in some classes of repetition work, cylindrical workpieces are usually held in a collet inserted into the spindle and secured either by a drawbar, or by a collet closing cap on the spindle. Suitable collets may also be used to mount square or hexagonal workpieces. In precision toolmaking work such collets are usually of the draw-in variety, where, as the collet is tightened, the workpiece moves slightly back into the headstock, whereas for most repetition work the dead length variety is preferred, as this ensures that the position of the workpiece does not move as the collet is tightened.

A soft workpiece (wooden) may be pinched between centers by using a spur drive at the headstock, which bites into the wood and imparts torque to it.



Live center (top); dead center (bottom)

A soft dead center is used in the headstock spindle as the work rotates with the centre. Because the centre is soft it can be trued in place before use. The included angle is 60°. Traditionally, a hard dead center is used together with suitable lubricant in the tailstock to support the workpiece. In modern practice the dead center is frequently replaced by a live center, as it turns freely with the workpiece — usually on ball bearings — reducing the frictional heat, especially important at high speeds. When clear facing a long length of material it must be supported at both ends. This can be achieved by the use of a travelling or fixed steady. If a steady is not available, the end face being worked on may be supported by a dead (stationary) half centre. A half centre has a flat surface machined across a broad section of half of its diameter at the pointed end. A small section of the tip of the dead centre is retained to ensure concentricity. Lubrication must be applied at this point of contact and tail stock pressure reduced. A lathe carrier or lathe dog may also be employed when turning between two centers.

In woodturning, one variation of a live center is a cup center, which is a cone of metal surrounded by an annular ring of metal that decreases the chances of the workpiece splitting.

A circular metal plate with even spaced holes around the periphery, mounted to the spindle, is called an "index plate". It can be used to rotate the spindle to a precise angle, then lock it in place, facilitating repeated auxiliary operations done to the workpiece.

Other accessories, including items such as taper turning attachments, knurling tools, vertical slides, fixed and traveling steadies, etc., increase the versatility of a lathe and the range of work it may perform.

Modes of use

When a workpiece is fixed between the headstock and the tailstock, it is said to be "between centers". When a workpiece is supported at both ends, it is more stable, and more force may be applied to the workpiece, via tools, at a right angle to the axis of rotation, without fear that the workpiece may break loose.

When a workpiece is fixed only to the spindle at the headstock end, the work is said to be "face work". When a workpiece is supported in this manner, less force may be applied to the workpiece, via tools, at a right angle to the axis of rotation, lest the workpiece rip free. Thus, most work must be done axially, towards the headstock, or at right angles, but gently.

When a workpiece is mounted with a certain axis of rotation, worked, then remounted with a new axis of rotation, this is referred to as "eccentric turning" or "multi axis turning". The result is that various cross sections of the workpiece are rotationally symmetric, but the workpiece as a whole is not rotationally symmetric. This technique is used for camshafts, various types of chair legs.

Varieties

The smallest lathes are "jewelers lathes" or "watchmaker lathes", which are small enough that they may be held in one hand. The workpieces machined on a jeweler's lathes are metal, jeweler's lathes can be used with hand-held "graver" tools or with compound rests that attach to the lathe bed. Graver tools are generally supported by a T-rest, not fixed to a cross slide or compound rest. The work is usually held in a collet. Common spindle bore sizes are 6 mm, 8 mm and 10 mm. The term W/W refers to the Webster/Whitcomb collet and lathe, invented by the American Watch Tool Company of Waltham, Massachusetts. Most lathes commonly referred to as watchmakers lathes are of this design. In 1909, the American Watch Tool company introduced the Magnus type collet (a 10-mm body size collet) using a lathe of the same basic design, the Webster/Whitcomb Magnus. (F.W.Derbyshire, Inc. retains the trade names Webster/Whitcomb and Magnus and still produces these collets.) Two bed patterns are common: the WW (Webster Whitcomb) bed, a truncated triangular prism (found only on 8 and 10 mm watchmakers' lathes); and the continental D-style bar bed (used on both 6 mm and 8 mm lathes by firms such as Lorch and Star). Other bed designs have been used, such a triangular prism on some Boley 6.5 mm lathes, and a V-edged bed on IME's 8 mm lathes.

Smaller metalworking lathes that are larger than jewelers' lathes and can sit on a bench or table, but offer such features as tool holders and a screw-cutting gear train are called hobby lathes, and larger versions, "bench lathes". Even larger lathes offering similar features for producing or modifying individual parts are called "engine lathes". Lathes of these types do not have additional integral features for repetitive production, but rather are used for individual part production or modification as the primary role.

Lathes of this size that are designed for mass manufacture, but not offering the versatile screw-cutting capabilities of the engine or bench lathe, are referred to as "second operation" lathes.

Lathes with a very large spindle bore and a chuck on both ends of the spindle are called "oil field lathes".

Fully automatic mechanical lathes, employing cams and gear trains for controlled movement, are called screw machines.

Lathes that are controlled by a computer are CNC lathes.

Lathes with the spindle mounted in a vertical configuration, instead of horizontal configuration, are called vertical lathes or vertical boring machines. They are used where very large diameters must be turned, and the workpiece (comparatively) is not very long.

A lathe with a cylindrical tailstock that can rotate around a vertical axis, so as to present different tools towards the headstock (and the workpiece) are turret lathes.

A lathe equipped with indexing plates, profile cutters, spiral or helical guides, etc., so as to enable ornamental turning is an ornamental lathe.

Various combinations are possible: for example, a vertical lathe have CNC as well (such as a CNC VTL).

Lathes can be combined with other machine tools, such as a drill press or vertical milling machine. These are usually referred to as combination lathes.

Major categories

Woodworking lathes

A modern woodworking lathe.

Woodworking lathes are the oldest variety. All other varieties are descended from these simple lathes. An adjustable horizontal metal rail - the tool rest - between the material and the operator accommodates the positioning of shaping tools, which are usually hand-held. With wood, it is common practice to press and slide sandpaper against the still-spinning object after shaping to smooth the surface made with the metal shaping tools.

There are also woodworking lathes for making bowls and plates, which have no horizontal metal rail, as the bowl or plate needs only to be held by one side from a metal face plate. Without this rail, there is very little restriction to the width of the piece being turned. Further detail can be found on the woodturning page.

Metalworking lathes

A metalworking lathe

In a metalworking lathe, metal is removed from the workpiece using a hardened cutting tool, which is usually fixed to a solid moveable mounting, either a toolpost or a turret, which is then moved against the workpiece using handwheels and/or computer controlled motors. These (cutting) tools come in a wide range of sizes and shapes depending upon their application. Some common styles are diamond, round, square and triangular.

The toolpost is operated by leadscrews that can accurately position the tool in a variety of planes. The toolpost may be driven manually or automatically to produce the roughing and finishing cuts required to *turn* the workpiece to the desired shape and dimensions, or for cutting threads, worm gears, etc. Cutting fluid may also be pumped to the cutting site to provide cooling, lubrication and clearing of swarf from the workpiece. Some lathes may be operated under control of a computer for mass production of parts.

Manually controlled metalworking lathes are commonly provided with a variable ratio gear train to drive the main leadscrew. This enables different thread pitches to be cut. On some older lathes or more affordable new lathes, the gear trains are changed by swapping gears with various numbers of teeth onto or off of the shafts, while more modern or expensive manually controlled lathes have a **quick change box** to provide commonly used ratios by the operation of a lever. CNC lathes use computers and servomechanisms to regulate the rates of movement.

On manually controlled lathes, the thread pitches that can be cut are, in some ways, determined by the pitch of the leadscrew: A lathe with a metric leadscrew will readily cut metric threads (including BA), while one with an imperial leadscrew will readily cut imperial unit based threads such as BSW or UTS (UNF,UNC). This limitation is not insurmountable, because a 127-tooth gear, called a transposing gear, is used to translate between metric and inch thread pitches. However, this is optional equipment that many lathe owners do not own. It is also a larger changewheel than the others, and on some lathes may be larger than the changewheel mounting banjo is capable of mounting.

The workpiece may be supported between a pair of points called centres, or it may be bolted to a faceplate or held in a chuck. A chuck has movable jaws that can grip the workpiece securely.

There are some effects on material properties when using a metalworking lathe. There are few chemical or physical effects, but there are many mechanical effects, which include residual stress, microcracks, workhardening, and tempering in hardened materials.

Cue lathes

Cue lathes function similar to turning and spinning lathes allowing for a perfectly radially-symmetrical cut for billiard cues. They can also be used to refinish cues that have been worn over the years.

Glassworking lathes

Glassworking lathes are similar in design to other lathes, but differ markedly in how the workpiece is modified. Glassworking lathes slowly rotate a hollow glass vessel over a fixed or variable temperature flame. The source of the flame may be either hand-held, or mounted to a banjo/cross slide that can be moved along the lathe bed. The flame serves to soften the glass being worked, so that the glass in a specific area of the workpiece becomes malleable, and subject to forming either by inflation ("glassblowing"), or by deformation with a heat resistant tool. Such lathes usually have two headstocks with chucks holding the work, arranged so that they both rotate together in unison. Air can be introduced through the headstock chuck spindle for glassblowing. The tools to deform the glass and tubes to blow (inflate) the glass are usually handheld.

In diamond turning, a computer-controlled lathe with a diamond-tipped tool is used to make precision optical surfaces in glass or other optical materials. Unlike conventional optical grinding, complex aspheric surfaces can be machined easily. Instead of the dovetailed ways used on the tool slide of a metal turning lathe, the ways typically float on air bearings and the position of the tool is measured by optical interferometry to achieve the necessary standard of precision for optical work. The finished work piece usually requires a small amount subsequent polishing by conventional techniques to achieve a finished surface suitably smooth for use in a lens, but the rough grinding time is significantly reduced for complex lenses.

Metal spinning lathes

In metal spinning, a disk of sheet metal is held perpendicularly to the main axis of the lathe, and tools with polished tips (*spoons*) are hand held, but levered by hand against fixed posts, to develop large amounts of torque/pressure that deform the spinning sheet of metal.

Metal spinning lathes are almost as simple as woodturning lathes (and, at this point, lathes being used for metal spinning almost always *are* woodworking lathes). Typically, metal spinning lathes require a user-supplied rotationally symmetric mandrel, usually made of wood, which serves as a template onto which the workpiece is moulded (non-symmetric shapes *can* be done, but it is a very advanced technique). For example, if you want to make a sheet metal bowl, you need a solid chunk of wood in the shape of the bowl; if you want to make a vase, you need a solid template of a vase, etc.

Given the advent of high speed, high pressure, industrial die forming, metal spinning is less common now than it once was, but still a valuable technique for producing one-off prototypes or small batches where die forming would be uneconomical.

Ornamental turning lathes

The ornamental turning lathe was developed around the same time as the industrial screwcutting lathe in the nineteenth century. It was used not for making practical objects, but for decorative work - *ornamental turning*. By using accessories such as the horizontal and vertical cutting frames, eccentric chuck and elliptical chuck, solids of extraordinary complexity may be produced by various generative procedures.

A special purpose lathe, the Rose engine lathe is also used for ornamental turning, in particular for engine turning, typically in precious metals, for example to decorate pocket watch cases. As well as a wide range of accessories, these lathes usually have complex dividing arrangements to allow the exact rotation of the mandrel. Cutting is usually carried out by rotating cutters, rather than directly by the rotation of the work itself. Because of the difficulty of polishing such work, the materials turned, such as wood or ivory, are usually quite soft, and the cutter has to be exceptionally sharp. The finest ornamental lathes are generally considered to be those made by Holtzapffel around the turn of the 19th century.

Reducing lathe

Many types of lathes can be equipped with accessory components to allow them to reproduce an item: the original item is mounted on one spindle, the blank is mounted on another, and as both turn in synchronized manner, one end of an arm "reads" the original and the other end of the arm "carves" the duplicate.

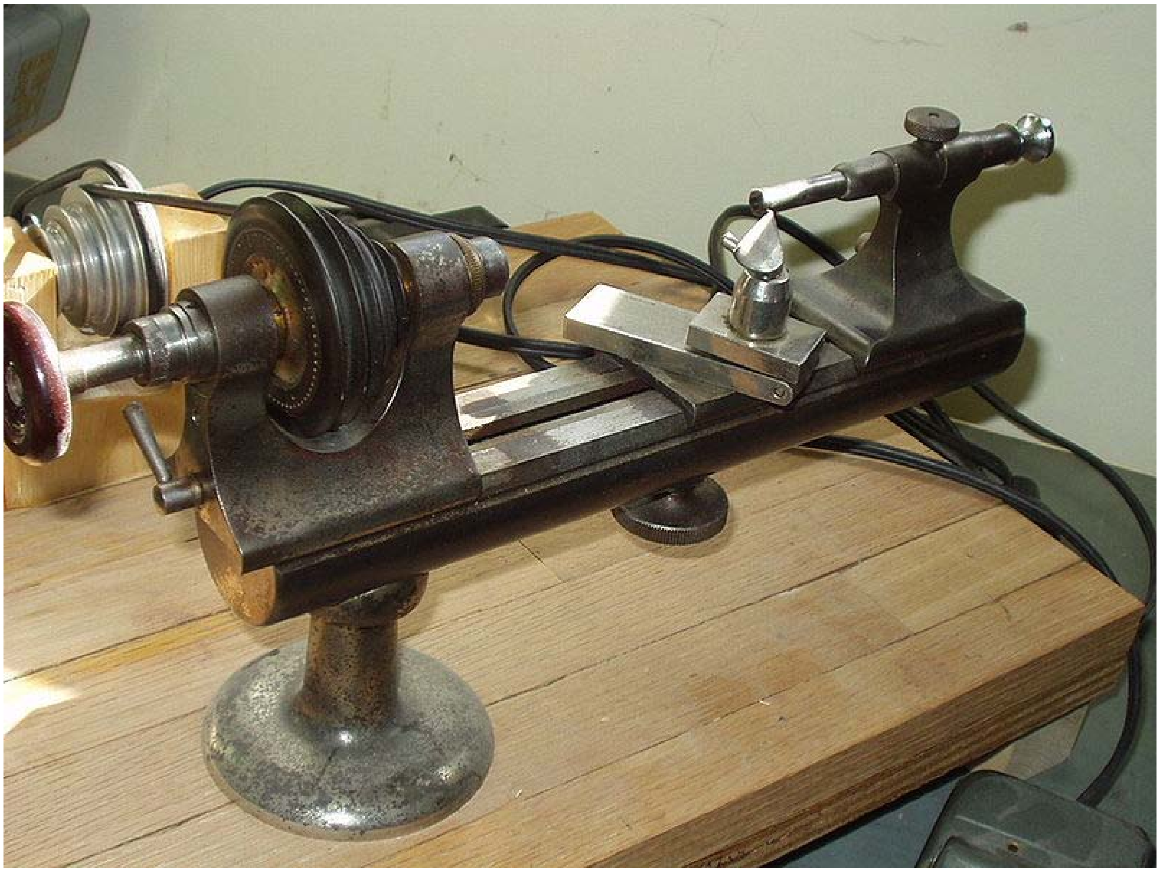
A **reducing lathe** is a specialized lathe that is designed with this feature, and which incorporates a mechanism similar to a pantograph, so that when the "reading" end of the arm reads a detail that measures one inch (for example), the cutting end of the arm creates an analogous detail that is (for example) one quarter of an inch (a 4:1 reduction, although given appropriate machinery and appropriate settings, any reduction ratio is possible).

Reducing lathes are used in coin-making, where a plaster original (or an epoxy master made from the plaster original, or a copper shelled master made from the plaster original, etc.) is duplicated and reduced on the reducing lathe, generating a master die.

Rotary lathes

A lathe in which softwood, like spruce or pine, or hardwood, like birch, logs are turned against a very sharp blade and peeled off in one continuous or semi-continuous roll. Invented by Immanuel Nobel (father of the more famous Alfred Nobel). The first such lathes were set up in the United States in the mid-19th century. The product is called wood veneer and it is used for finishing chipboard objects and making plywood.

Watchmaker's lathes



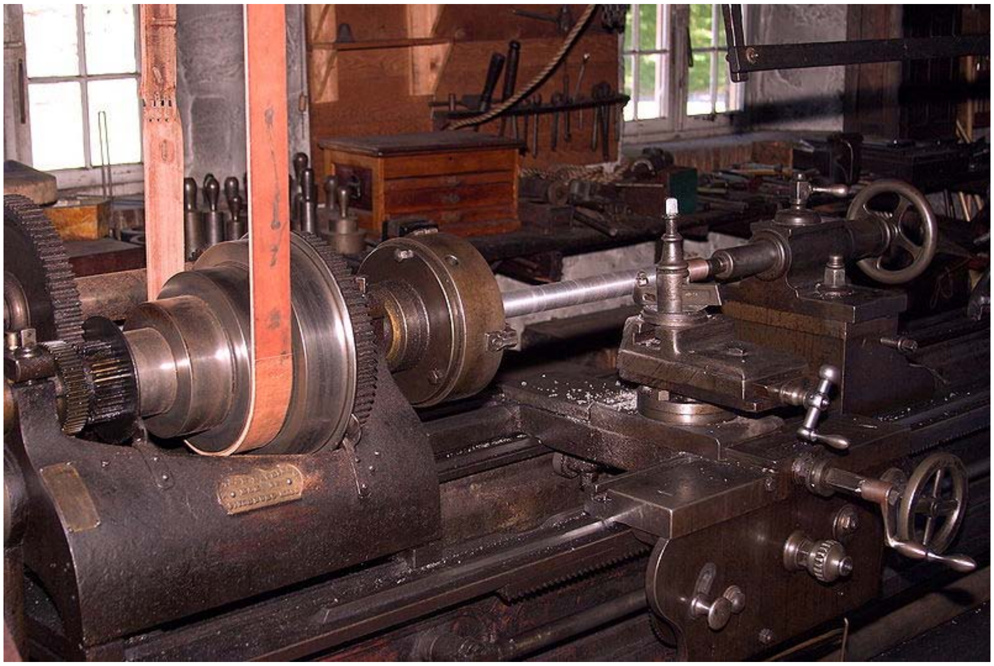
Watchmaker's lathe

Watchmakers lathes are delicate but precise metalworking lathes, usually without provision for screwcutting, and are still used by horologists for work such as the turning of balance shafts. A handheld tool called a graver is often used in preference to a slide mounted tool. The original watchmaker's turns was a simple dead-centre lathe with a moveable rest and two loose headstocks. The workpiece would be rotated by a bow, typically of horsehair, wrapped around it.

Examples of lathes

Small metalworking lathe

Large old lathe



Belt-driven metalworking lathe in the machine shop at Hagley Museum

Examples of work produced from a lathe

Lathe exercise

Turned chess pieces

Chapter 4

Propeller

Rotating the Hamilton Standard 54H60 propeller on a US Navy EP-3E Orion's number four engine as part of pre-flight checks

A **propeller** is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and air or water is accelerated behind the blade. Propeller dynamics can be modeled by both Bernoulli's principle and Newton's third law. A propeller is often colloquially known as **screw** both in aviation and maritime.

History

Ship propeller from 1843. Designed by C F Wahlgren based on one of John Ericsson propellers. It was fitted to the steam ship s/s *Flygfisken* built at the Motala dockyard.

The principle employed in using a screw propeller is used in sculling. It is part of the skill of propelling a Venetian gondola but was used in a less refined way in other parts of

Europe and probably elsewhere. For example, propelling a canoe with a single paddle using a "j-stroke" involves a related but not identical technique. In China, sculling, called "lu", was also used by the 3rd century AD.

In sculling, a single blade is moved through an arc, from side to side taking care to keep presenting the blade to the water at the effective angle. The innovation introduced with the screw propeller was the extension of that arc through more than 360° by attaching the blade to a rotating shaft. Propellers can have a single blade, but in practice there are nearly always more than one so as to balance the forces involved.

The origin of the actual screw propeller starts with Archimedes, who used a screw to lift water for irrigation and bailing boats, so famously that it became known as Archimedes' screw. It was probably an application of spiral movement in space (spirals were a special study of Archimedes) to a hollow segmented water-wheel used for irrigation by Egyptians for centuries. Leonardo da Vinci adopted the principle to drive his theoretical helicopter, sketches of which involved a large canvas screw overhead.

In 1784, J. P. Paucton proposed a gyrocopter-like aircraft using similar screws for both lift and propulsion. At about the same time, James Watt proposed using screws to propel boats, although he did not use them for his steam engines. This was not his own invention, though; Toogood and Hays had patented it a century earlier, and it had become a common use as a means of propelling boats since that time.

By 1827, Czech constructor Josef Ressel had invented a screw propeller which had multiple blades fastened around a conical base; this new method of propulsion allowed steam ships to travel at much greater speeds without using sails thereby making ocean travel faster (first tests with the Austro-Hungarian Navy).

John Patch, a mariner in Yarmouth, Nova Scotia developed a two-bladed, fan-shaped propeller in 1832 and publicly demonstrated it in 1833, propelling a row boat across Yarmouth Harbour and a small coastal schooner at Saint John, New Brunswick, but his patent application in the United States was rejected until 1849 because he was not American citizen His efficient design drew praise in American scientific circles but by this time there were multiple competing versions of the marine propeller.

In 1835, when Francis Pettit Smith discovered a new way of building propellers. Up to that time, propellers were literally screws, of considerable length. But during the testing of a boat propelled by one, the screw snapped off, leaving a fragment shaped much like a modern boat propeller. The boat moved faster with the broken propeller. At about the same time, Frédéric Sauvage and John Ericsson applied for patents on vaguely similar, although less efficient shortened-screw propellers, leading to an apparently permanent controversy as to who the official inventor is among those three men. Ericsson became widely famous when he built the *Monitor*, an armoured battleship that in 1862 fought the Confederate States' *Virginia* in an American Civil War sea battle.

The first screw propeller to be powered by a gasoline engine, fitted to a small boat (now known as a powerboat) was installed by Frederick Lanchester, also from Birmingham. This was tested in Oxford. The first 'real-world' use of a propeller was by David Bushnell, who used hand-powered screw propellers to navigate his submarine "Turtle" in 1776.

The superiority of screw against paddles was taken up by navies. Trials with Smith's SS *Archimedes*, the first steam driven screw, led to the famous tug-of-war competition in 1845 between the screw-driven HMS *Rattler* and the paddle steamer HMS *Alecto*; the former pulling the latter backward.

In the second half of the nineteenth century, several theories were developed. The momentum theory or Disk actuator theory—a theory describing a mathematical model of an ideal propeller—was developed by W.J.M. Rankine (1865), Alfred George Greenhill (1888) and R.E. Froude (1889). The propeller is modeled as an infinitely thin disc, inducing a constant velocity along the axis of rotation. This disc creates a flow around the propeller. Under certain mathematical premises of the fluid, there can be extracted a mathematical connection between power, radius of the propeller, torque and induced velocity. Friction is not included.

The blade element theory (BET) is a mathematical process originally designed by William Froude (1878), David W. Taylor (1893) and Stefan Drzewiecki to determine the behavior of propellers. It involves breaking an airfoil down into several small parts then determining the forces on them. These forces are then converted into accelerations, which can be integrated into velocities and positions.

A World War I wooden aircraft propeller on a workbench.

The twisted airfoil (aerofoil) shape of modern aircraft propellers was pioneered by the Wright brothers. While both the blade element theory and the momentum theory had their supporters, the Wright brothers were able to combine both theories. They found that a propeller is essentially the same as a wing and so were able to use data collated from their earlier wind tunnel experiments on wings. They also found that the relative angle of attack from the forward movement of the aircraft was different for all points along the length of the blade, thus it was necessary to introduce a twist along its length. Their original propeller blades are only about 5% less efficient than the modern equivalent, some 100 years later.

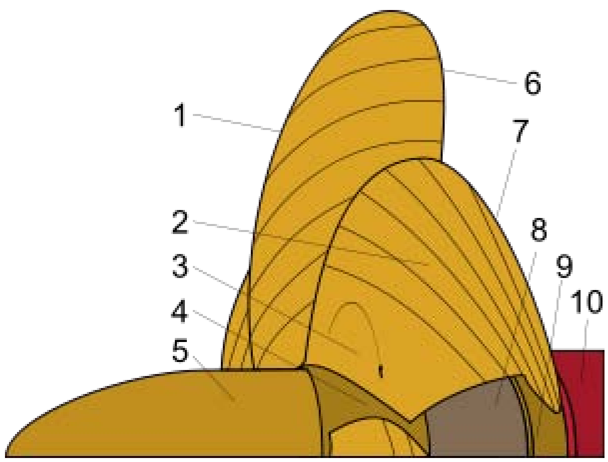
Alberto Santos Dumont was another early pioneer, having designed propellers before the Wright Brothers (albeit not as efficient) for his airships. He applied the knowledge he gained from experiences with airships to make a propeller with a steel shaft and aluminium blades for his 14 bis biplane. Some of his designs used a bent aluminium sheet for blades, thus creating an airfoil shape. These are heavily undercambered because of this and combined with the lack of a lengthwise twist made them less efficient than the Wright propellers. Even so, this was perhaps the first use of aluminium in the construction of an airscrew.

Aviation

Aircraft propellers convert rotary motion from piston engines or turboprops to provide propulsive force. They may be fixed or variable pitch. Early aircraft propellers were carved by hand from solid or laminated wood with later propellers being constructed from metal. The most modern propeller designs use high-technology composite materials.

Marine

Marine propeller nomenclature



1) Trailing edge	6) Leading edge
2) Face	7) Back
3) Fillet area	8) Propeller shaft
4) Hub or Boss	9) Stern tube bearing
5) Hub or Boss Cap	10) Stern tube

A propeller is the most common propulsor on ships, imparting momentum to a fluid which causes a force to act on the ship.

The ideal efficiency of any size propeller (free-tip) is that of an actuator disc in an ideal fluid. An actual marine propeller is made up of sections of helicoidal surfaces which act together 'screwing' through the water (hence the common reference to marine propellers as "screws"). Three, four, or five blades are most common in marine propellers, although designs which are intended to operate at reduced noise will have more blades. The blades are attached to a *boss* (hub), which should be as small as the needs of strength allow - with fixed pitch propellers the blades and boss are usually a single casting.

An alternative design is the controllable pitch propeller (CPP, or CRP for controllable-reversible pitch), where the blades are rotated normal to the drive shaft by additional machinery - usually hydraulics - at the hub and control linkages running down the shaft. This allows the drive machinery to operate at a constant speed while the propeller loading is changed to match operating conditions. It also eliminates the need for a reversing gear and allows for more rapid change to thrust, as the revolutions are constant. This type of propeller is most common on ships such as tugs where there can be enormous differences in propeller loading when towing compared to running free, a change which could cause conventional propellers to lock up as insufficient torque is generated. The downsides of a CPP/CRP include: the large hub which decreases the torque required to cause cavitation, the mechanical complexity which limits transmission power and the extra blade shaping requirements forced upon the propeller designer.

For smaller motors there are self-pitching propellers. The blades freely move through an entire circle on an axis at right angles to the shaft. This allows hydrodynamic and centrifugal forces to 'set' the angle the blades reach and so the pitch of the propeller.

A propeller that turns clockwise to produce forward thrust, when viewed from aft, is called right-handed. One that turns anticlockwise is said to be left-handed. Larger vessels often have twin screws to reduce *heeling torque*, counter-rotating propellers, the starboard screw is usually right-handed and the port left-handed, this is called outward turning. The opposite case is called inward turning. Another possibility is contra-rotating propellers, where two propellers rotate in opposing directions on a single shaft, or on separate shafts on nearly the same axis. One example of the latter is the CRP Azipod by the ABB Group. Contra-rotating propellers offer increased efficiency by capturing the energy lost in the tangential velocities imparted to the fluid by the forward propeller (known as "propeller swirl"). The flow field behind the aft propeller of a contra-rotating set has very little "swirl", and this reduction in energy loss is seen as an increased efficiency of the aft propeller.

Additional designs

An azimuthing propeller is a vertical axis propeller.

The blade outline is defined either by a projection on a plane normal to the propeller shaft (*projected outline*) or by setting the circumferential chord across the blade at a given radius against radius (*developed outline*). The outline is usually symmetrical about a given radial line termed the *median*. If the median is curved back relative to the direction of rotation the propeller is said to have *skew back*. The skew is expressed in terms of circumferential displacement at the blade tips. If the blade face in profile is not normal to the axis it is termed *raked*, expressed as a percentage of total diameter.

Each blade's pitch and thickness varies with radius, early blades had a flat face and an arced back (sometimes called a circular back as the arc was part of a circle), modern propeller blades have aerofoil sections. The *camber line* is the line through the mid-thickness of a single blade. The *camber* is the maximum difference between the camber line and the *chord* joining the trailing and leading edges. The camber is expressed as a percentage of the chord.

The radius of maximum thickness is usually forward of the mid-chord point with the blades thinning to a minimum at the tips. The thickness is set by the demands of strength and the ratio of thickness to total diameter is called *blade thickness fraction.*

The ratio of pitch to diameter is called *pitch ratio*. Due to the complexities of modern propellers a nominal pitch is given, usually a radius of 70% of the total is used.

Blade area is given as a ratio of the total area of the propeller disc, either as *developed blade area ratio* or *projected blade area ratio*.

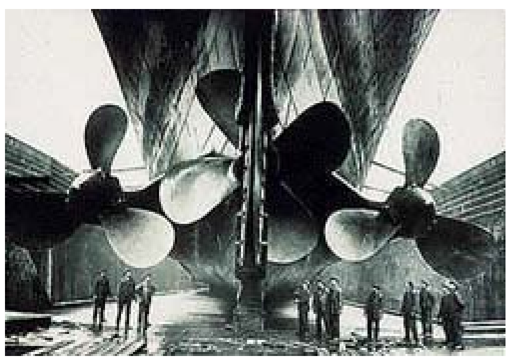
Transverse axis propellers

Most propellers have their axis of rotation parallel to the fluid flow. There have however been some attempts to power vehicles with the same principles behind vertical axis wind turbines, where the rotation is perpendicular to fluid flow. Most attempts have been unsuccessful. Blades that can vary their angle of attack during rotation have aerodynamics similar to flapping flight. Flapping flight is still poorly understood and almost never seriously used in engineering because of the strong coupling of lift, thrust and control forces.

The fanwing is one of the few types that has actually flown. It takes advantage of the trailing edge of an airfoil to help encourage the circulation necessary for lift.

The Voith-Schneider propeller pictured below is another successful example, operating in water.

History of ship and submarine screw propellers



Propellers of the *Titanic*: 2 triple-blade and 1 quadruple-blade at center

A propeller from the *Lusitania*

Propeller on a modern mid-sized merchant vessel

James Watt of Scotland is generally credited with applying the first screw propeller to an engine, an early steam engine, beginning the use of an hydrodynamic screw for propulsion.

Mechanical ship propulsion began with the steam ship. The first successful ship of this type is a matter of debate; candidate inventors of the 18th century include William Symington, the Marquis de Jouffroy, John Fitch and Robert Fulton, however William

Symington's ship the *Charlotte Dundas* is regarded as the world's "first practical steamboat". Paddlewheels as the main motive source became standard on these early vessels. Robert Fulton had tested, and rejected, the screw propeller.

Sketch of hand-cranked vertical and horizontal screws used in Bushnell's *Turtle*, 1775

The screw (as opposed to paddlewheels) was introduced in the latter half of the 18th century. David Bushnell's invention of the submarine (Turtle) in 1775 used hand-powered screws for vertical and horizontal propulsion. The Bohemian engineer Josef Ressel designed and patented the first practicable screw propeller in 1827. Francis Pettit Smith tested a similar one in 1836. In 1839, John Ericsson introduced practical screw propulsion into the United States. Mixed paddle and propeller designs were still being used at this time (*vide* the 1858 *SS Great Eastern*).

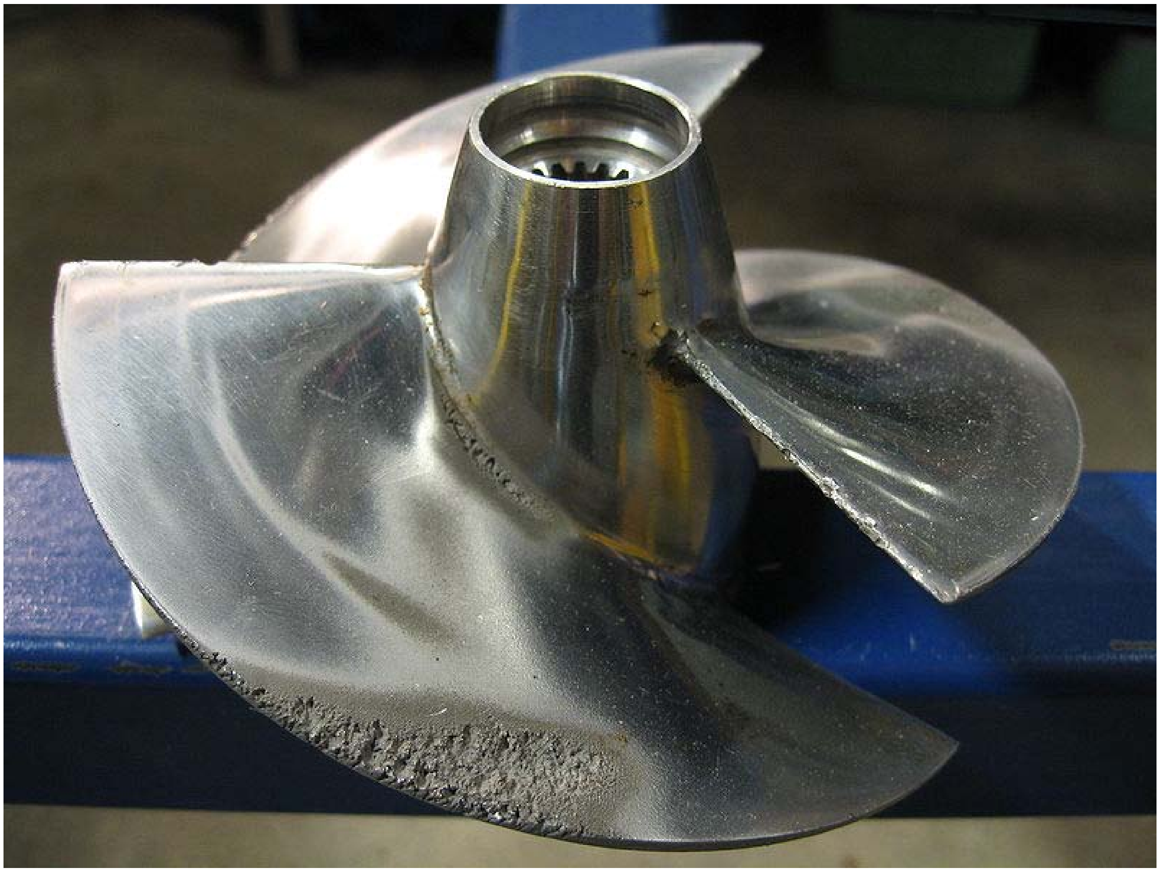
In 1848 the British Admiralty held a tug of war contest between a propeller driven ship, *Rattler*, and a paddle wheel ship, *Alecto*. *Rattler* won, towing *Alecto* astern at 2.5 knots (4.6 km/h), but it was not until the early 20th century that paddle propelled vessels were entirely superseded. The screw propeller replaced the paddles owing to its greater efficiency, compactness, less complex power transmission system, and reduced susceptibility to damage (especially in battle)

Voith-Schneider propeller

Initial designs owed much to the ordinary screw from which their name derived - early propellers consisted of only two blades and matched in profile the length of a single screw rotation. This design was common, but inventors endlessly experimented with different profiles and greater numbers of blades. The propeller screw design stabilized by the 1880s.

In the early days of steam power for ships, when both paddle wheels and screws were in use, ships were often characterized by their type of propellers, leading to terms like screw steamer or screw sloop.

Propellers are referred to as "lift" devices, while paddles are "drag" devices.



Cavitation damage evident on the propeller of a personal watercraft.

Marine propeller cavitation

Cavitation can occur if an attempt is made to transmit too much power through the screw, or if the propeller is operating at a very high speed. Cavitation can occur in many ways on a propeller. The two most common types of propeller cavitation are suction side surface cavitation and tip vortex cavitation.

Suction side surface cavitation forms when the propeller is operating at high rotational speeds or under heavy load (high blade lift coefficient). The pressure on the upstream surface of the blade (the "suction side") can drop below the vapour pressure of the water, resulting in the formation of a pocket of vapour. Under such conditions, the change in pressure between the downstream surface of the blade (the "pressure side") and the suction side is limited, and eventually reduced as the extent of cavitation is increased. When most of the blade surface is covered by cavitation, the pressure difference between the pressure side and suction side of the blade drops considerably, and thrust produced by the propeller drops. This condition is called "thrust breakdown". This effect wastes energy, makes the propeller "noisy" as the vapour bubbles collapse, and most seriously, erodes the screw's surface due to localized shock waves against the blade surface.

Tip vortex cavitation is caused by the extremely low pressures formed at the core of the tip vortex. The tip vortex is caused by fluid wrapping around the tip of the propeller; from the pressure side to the suction side. This video demonstrates tip vortex cavitation well. Tip vortex cavitation typically occurs before suction side surface cavitation and is less damaging to the blade, since this type of cavitation doesn't collapse on the blade, but some distance downstream.

Cavitation can be used as an advantage in design of very high performance propellers, in form of the supercavitating propeller. In this case, the blade section is designed such that the pressure side stays wetted while the suction side is completely covered by cavitation vapor. Because the suction side is covered with vapor instead of water it encounters very low viscous friction, making the supercavitating (SC) propeller comparably efficient at high speed. The shaping of SC blade sections however, make it inefficient at low speeds, when the suction side of the blade is wetted.

A similar, but quite separate issue, is *ventilation,* which occurs when a propeller operating near the surface draws air into the blades, causing a similar loss of power and shaft vibration, but without the related potential blade surface damage caused by cavitation. Both effects can be mitigated by increasing the submerged depth of the propeller: cavitation is reduced because the hydrostatic pressure increases the margin to the vapor pressure, and ventilation because it is further from surface waves and other air pockets that might be drawn into the slipstream.

14-ton propeller from *Voroshilov* a Kirov class cruiser on display in Sevastopol

Forces acting on an aerofoil

The force (F) experienced by an aerofoil blade is determined by its area (A), chord (c), velocity (V) and the angle of the aerofoil to the flow, called *angle of attack* (α), where:

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

The force has two parts - that normal to the direction of flow is *lift* (L) and that in the direction of flow is *drag* (D). Both are expressed non-dimensionally as:

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

Each coefficient is a function of the angle of attack and Reynolds' number. As the angle of attack increases lift rises rapidly from the *no lift angle* before slowing its increase and then decreasing, with a sharp drop as the *stall angle* is reached and flow is disrupted. Drag rises slowly at first and as the rate of increase in lift falls and the angle of attack increases drag increases more sharply.

For a given strength of circulation (τ), Lift = $L = \rho V \tau$. The effect of the flow over and the circulation around the aerofoil is to reduce the velocity over the face and increase it over the back of the blade. If the reduction in pressure is too much in relation to the ambient pressure of the fluid, *cavitation* occurs, bubbles form in the low pressure area and are moved towards the blade's trailing edge where they collapse as the pressure increases, this reduces propeller efficiency and increases noise. The forces generated by the bubble collapse can cause permanent damage to the surfaces of the blade.

Propeller thrust

Single blade

Taking an arbitrary radial section of a blade at *r*, if revolutions are *N* then the rotational velocity is $2\pi N r$. If the blade was a complete screw it would advance through a solid at the rate of *NP*, where *P* is the pitch of the blade. In water the advance speed is rather lower, V_a, the difference, or *slip ratio*, is:

$$\text{Slip} = \frac{NP - V_a}{NP} = 1 - \frac{J}{p}$$

where $J = \frac{V_a}{ND}$ is the *advance coefficient*, and $p = \frac{P}{D}$ is the *pitch ratio*.

The forces of lift and drag on the blade, *dA*, where force normal to the surface is *dL*:

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

where:

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

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

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

where:

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

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

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

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

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

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

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

which can be integrated as before.

The total thrust power of the propeller is proportional to TV_a and the shaft power to $2\pi NQ$. So efficiency is $\frac{TV_a}{2\pi NQ}$. The blade efficiency is in the ratio between thrust and torque:

$$\text{blade element efficiency} = \frac{V_a}{2\pi Nr} \cdot \frac{1}{\tan(\varphi + \beta)}$$

showing that the blade efficiency is determined by its momentum and its qualities in the form of angles φ and β, where β is the ratio of the drag and lift coefficients.

This analysis is simplified and ignores a number of significant factors including interference between the blades and the influence of tip vortices.

Thrust and torque

The thrust, *T*, and torque, *Q*, depend on the propeller's diameter, *D*, revolutions, *N*, and rate of advance, V_a, together with the character of the fluid in which the propeller is operating and gravity. These factors create the following non-dimensional relationship:

$$T = \rho V^2 D^2 [f_1(\frac{ND}{V_a}), f_2(\frac{v}{V_a D}), f_3(\frac{gD}{V_a^2})]$$

where f_1 is a function of the advance coefficient, f_2 is a function of the Reynolds' number, and f_3 is a function of the Froude number. Both f_2 and f_3 are likely to be small in comparison to f_1 under normal operating conditions, so the expression can be reduced to:

$$T = \rho V_a^2 D^2 \times f_r(\frac{ND}{V_a})$$

For two identical propellers the expression for both will be the same. So with the propellers T_1,T_2, and using the same subscripts to indicate each propeller:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{V_{a1}^2}{V_{a2}^2} \times \frac{D_1^2}{D_2^2}$$

For both Froude number and advance coefficient:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{D_1^3}{D_2^3} = \frac{\rho_1}{\rho_2} \lambda^3$$

where λ is the ratio of the linear dimensions.

Thrust and velocity, at the same Froude number, give thrust power:

$$\frac{P_{T1}}{P_{T2}} = \frac{\rho_1}{\rho_2}\lambda^{3.5}$$

For torque:

$$Q = \rho V_a^2 D^3 \times f_q\left(\frac{ND}{V_a}\right)$$

...

Actual performance

When a propeller is added to a ship its performance is altered; there is the mechanical losses in the transmission of power; a general increase in total resistance; and the hull also impedes and renders non-uniform the flow through the propeller. The ratio between a propeller's efficiency attached to a ship (P_D) and in open water (P'_D) is termed *relative rotative efficiency.*

The *overall propulsive efficiency* (an extension of *effective power* (P_E)) is developed from the *propulsive coefficient* (PC), which is derived from the installed shaft power (P_S) modified by the effective power for the hull with appendages (P'_E), the propeller's thrust power (P_T), and the relative rotative efficiency.

P'_E/P_T = hull efficiency = η_H
P_T/P'_D = propeller efficiency = η_O
P'_D/P_D = relative rotative efficiency = η_R
P_D/P_S = shaft transmission efficiency

Producing the following:

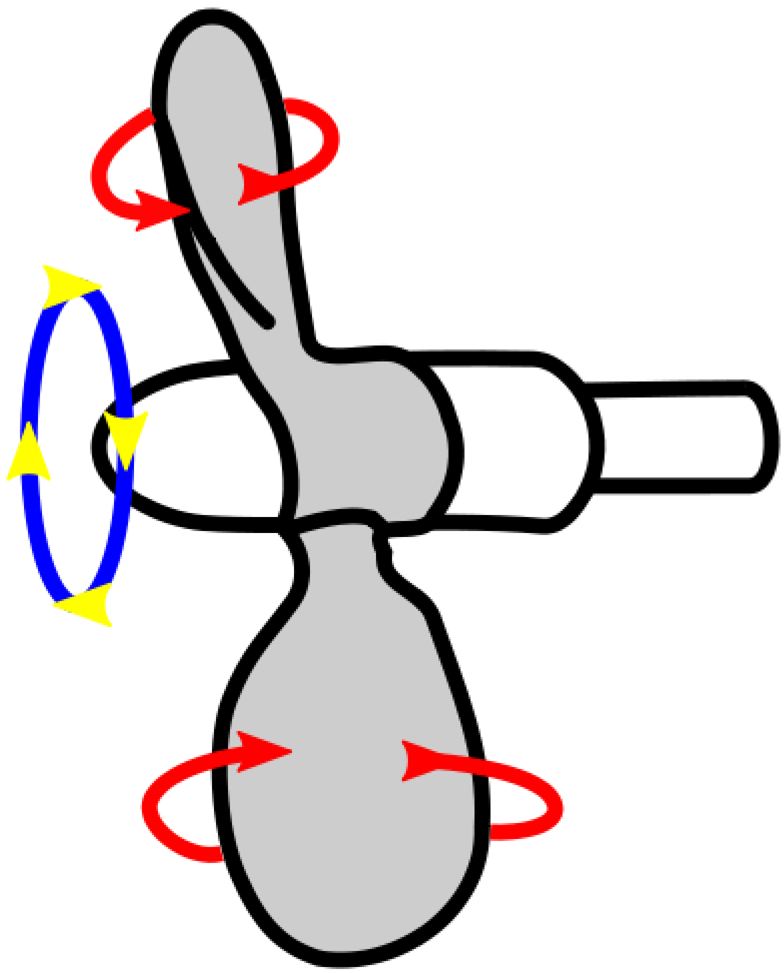
$$PC = \left(\frac{\eta_H \cdot \eta_O \cdot \eta_R}{\text{appendage coefficient}}\right) \cdot \text{transmission efficiency}$$

The terms contained within the brackets are commonly grouped as the *quasi-propulsive coefficient* (QPC, η_D). The QPC is produced from small-scale experiments and is modified with a load factor for full size ships.

Wake is the interaction between the ship and the water with its own velocity relative to the ship. The wake has three parts: the velocity of the water around the hull; the boundary layer between the water dragged by the hull and the surrounding flow; and the waves created by the movement of the ship. The first two parts will reduce the velocity of water into the propeller, the third will either increase or decrease the velocity depending on whether the waves create a crest or trough at the propeller.

Types of marine propellers

Controllable pitch propeller



A controllable pitch propeller

At present, one of the newest and best type of propeller is the controllable pitch propeller. This propeller has several advantages with ships. These advantages include: the least drag depending on the speed used, the ability to move the sea vessel backwards, and the ability to use the "vane"-stance, which gives the least water resistance when not using the propeller (e.g. when the sails are used instead).

Skewback propeller

An advanced type of propeller used on German Type 212 submarines is called a **skewback propeller**. As in the scimitar blades used on some aircraft, the blade tips of a skewback propeller are swept back against the direction of rotation. In addition, the blades are tilted rearward along the longitudinal axis, giving the propeller an overall cup-shaped appearance. This design preserves thrust efficiency while reducing cavitation, and thus makes for a quiet, stealthy design.

Modular propeller

A modular propeller provides more control over the boats performance. There is no need to change an entire prop, when there is an opportunity to only change the pitch or the damaged blades. Being able to adjust pitch will allow for boaters to have better performance while in different altitudes, water sports, and/or cruising.

Protection of small engines

A failed rubber bushing in an outboard's propeller

For smaller engines, such as outboards, where the propeller is exposed to the risk of collision with heavy objects, the propeller often includes a device which is designed to fail when over loaded; the device or the whole propeller is sacrificed so that the more expensive transmission and engine are not damaged.

Typically in smaller (less than 10 hp/7.5 kW) and older engines, a narrow shear pin through the drive shaft and propeller hub transmits the power of the engine at normal loads. The pin is designed to shear when the propeller is put under a load that could damage the engine. After the pin is sheared the engine is unable to provide propulsive power to the boat until an undamaged shear pin is fitted. Note that some shear pins used to have shear grooves machined into them. Nowadays the grooves tend to be omitted. The result of this oversight is that the torque required to shear the pin rises as the cutting edges of the propeller bushing and shaft become blunted. Eventually the gears will strip instead.

In larger and more modern engines, a rubber bushing transmits the torque of the drive shaft to the propeller's hub. Under a damaging load the friction of the bushing in the hub is overcome and the rotating propeller slips on the shaft preventing overloading of the engine's components. After such an event the rubber bushing itself may be damaged. If so, it may continue to transmit reduced power at low revolutions but may provide no power, due to reduced friction, at high revolutions. Also the rubber bushing may perish over time leading to its failure under loads below its designed failure load.

Whether a rubber bushing can be replaced or repaired depends upon the propeller; some cannot. Some can but need special equipment to insert the oversized bushing for an interference fit. Others can be replaced easily.

The "special equipment" usually consists of a tapered funnel, some kind of press and rubber lubricant (soap). Often the bushing can be drawn into place with nothing more complex than a couple of nuts, washers and "allscrew" (threaded bar). If one does not have access to a lathe an improvised funnel can be made from steel tube and car body filler! (as the filler is only subject to compressive forces it is able to do a good job) A more serious problem with this type of propeller is a "frozen-on" spline bushing which makes propeller removal impossible. In such cases the propeller has to be heated in order to deliberately destroy the rubber insert. Once the propeller proper is removed, the splined tube can be cut away with a grinder. A new spline bushing is of course required. To prevent the problem recurring the splines can be coated with anti-seize anti-corrosion compound.

In some modern propellers, a hard polymer insert called a *drive sleeve* replaces the rubber bushing. The splined or other non-circular cross section of the sleeve inserted between the shaft and propeller hub transmits the engine torque to the propeller, rather than friction. The polymer is weaker than the components of the propeller and engine so it fails before they do when the propeller is overloaded. This fails completely under excessive load but can easily be replaced.

Chapter 5

Turbine

A steam turbine with the case opened.

A **turbine** is a rotary engine that extracts energy from a fluid flow and converts it into useful work.

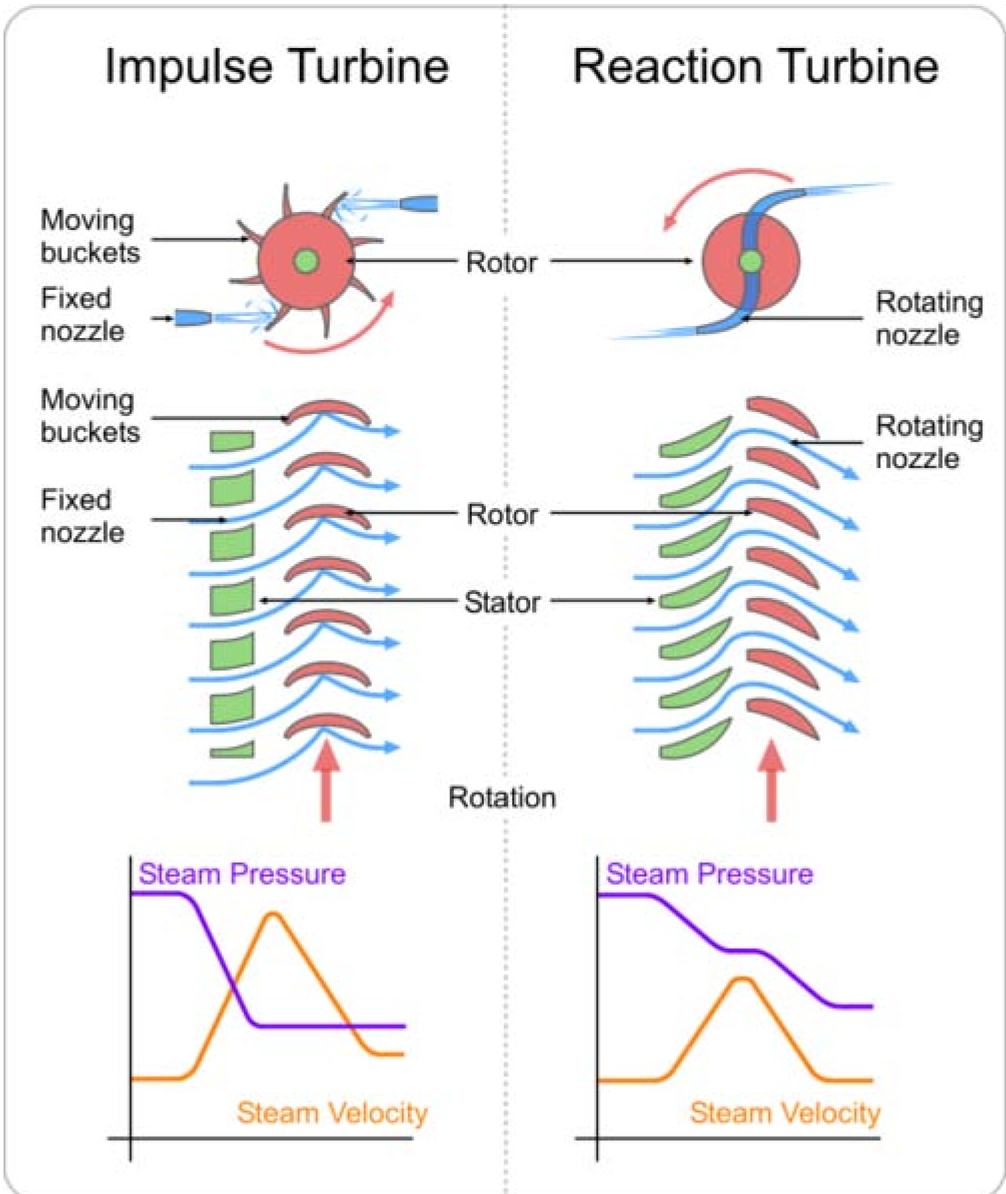
The simplest turbines have one moving part, a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they move and impart rotational energy to the rotor. Early turbine examples are windmills and water wheels.

Gas, steam, and water turbines usually have a casing around the blades that contains and controls the working fluid. Credit for invention of the steam turbine is given both to the British engineer Sir Charles Parsons (1854–1931), for invention of the reaction turbine and to Swedish engineer Gustaf de Laval (1845–1913), for invention of the impulse turbine. Modern steam turbines frequently employ both reaction and impulse in the same unit, typically varying the degree of reaction and impulse from the blade root to its periphery.

A device similar to a turbine but operating in reverse, i.e., driven, is a compressor or pump. The axial compressor in many gas turbine engines is a common example. Here again, both reaction and impulse are employed and again, in modern axial compressors, the degree of reaction and impulse will typically vary from the blade root to its periphery.

Claude Burdin coined the term from the Latin *turbo*, or vortex, during an 1828 engineering competition. Benoit Fourneyron, a student of Claude Burdin, built the first practical water turbine.

Theory of operation



A working fluid contains potential energy (pressure head) and kinetic energy (velocity head). The fluid may be compressible or incompressible. Several physical principles are employed by turbines to collect this energy:

Impulse turbines

> These turbines change the direction of flow of a high velocity fluid or gas jet. The resulting impulse spins the turbine and leaves the fluid flow with diminished kinetic energy. There is no pressure change of the fluid or gas in the turbine rotor blades (the moving blades), as in the case of a steam or gas turbine, all the pressure drop takes place in the stationary blades (the nozzles).

Before reaching the turbine, the fluid's *pressure head* is changed to *velocity head* by accelerating the fluid with a nozzle. Pelton wheels and de Laval turbines use this process exclusively. Impulse turbines do not require a pressure casement around the rotor since the fluid jet is created by the nozzle prior to reaching the blading on the rotor. Newton's second law describes the transfer of energy for impulse turbines.

Reaction turbines

> These turbines develop torque by reacting to the gas or fluid's pressure or mass. The pressure of the gas or fluid changes as it passes through the turbine rotor blades. A pressure casement is needed to contain the working fluid as it acts on the turbine stage(s) or the turbine must be fully immersed in the fluid flow (such as with wind turbines). The casing contains and directs the working fluid and, for water turbines, maintains the suction imparted by the draft tube. Francis turbines and most steam turbines use this concept. For compressible working fluids, multiple turbine stages are usually used to harness the expanding gas efficiently. Newton's third law describes the transfer of energy for reaction turbines.

In the case of steam turbines, such as would be used for marine applications or for land-based electricity generation, a Parsons type reaction turbine would require approximately double the number of blade rows as a de Laval type impulse turbine, for the same degree of thermal energy conversion. Whilst this makes the Parsons turbine much longer and heavier, the overall efficiency of a reaction turbine is slightly higher than the equivalent impulse turbine for the same thermal energy conversion.

Steam turbines and later, gas turbines developed continually during the 20th Century, continue to do so and in practice, modern turbine designs will use both reaction and impulse concepts to varying degrees whenever possible. Wind turbines use an airfoil to generate lift from the moving fluid and impart it to the rotor (this is a form of reaction). Wind turbines also gain some energy from the impulse of the wind, by deflecting it at an angle. Crossflow turbines are designed as an impulse machine, with a nozzle, but in low head applications maintain some efficiency through reaction, like a traditional water wheel. Turbines with multiple stages may utilize either reaction or impulse blading at high pressure. Steam Turbines were traditionally more impulse but continue to move towards reaction designs similar to those used in Gas Turbines. At low pressure the operating fluid medium expands in volume for small reductions in pressure. Under these conditions (termed Low Pressure Turbines) blading becomes strictly a reaction type design with the base of the blade solely impulse. The reason is due to the effect of the rotation speed for each blade. As the volume increases, the blade height increases, and the base of the blade spins at a slower speed relative to the tip. This change in speed forces a designer to change from impulse at the base, to a high reaction style tip.

Classical turbine design methods were developed in the mid 19th century. Vector analysis related the fluid flow with turbine shape and rotation. Graphical calculation methods were used at first. Formulae for the basic dimensions of turbine parts are well documented and a highly efficient machine can be reliably designed for any fluid flow condition. Some of the calculations are empirical or 'rule of thumb' formulae, and others are based on classical mechanics. As with most engineering calculations, simplifying assumptions were made.

Velocity triangles can be used to calculate the basic performance of a turbine stage. Gas exits the stationary turbine nozzle guide vanes at absolute velocity V_{a1}. The rotor rotates at velocity U. Relative to the rotor, the velocity of the gas as it impinges on the rotor entrance is V_{r1}. The gas is turned by the rotor and exits, relative to the rotor, at velocity V_{r2}. However, in absolute terms the rotor exit velocity is V_{a2}. The velocity triangles are constructed using these various velocity vectors. Velocity triangles can be constructed at any section through the blading (for example: hub , tip, midsection and so on) but are usually shown at the mean stage radius. Mean performance for the stage can be calculated from the velocity triangles, at this radius, using the Euler equation:

$$\Delta h = u \cdot \Delta v_w$$

Hence:

$$\left(\frac{\Delta h}{T}\right) = \left(\frac{u}{\sqrt{T}}\right) \cdot \left(\frac{\Delta v_w}{\sqrt{T}}\right)$$

where:

$\Delta h =$specific enthalpy drop across stage
$T =$turbine entry total (or stagnation) temperature
$u =$turbine rotor peripheral velocity
$\Delta v_w =$change in whirl velocity

The turbine pressure ratio is a function of $\left(\frac{\Delta H}{T}\right)$and the turbine efficiency.

Modern turbine design carries the calculations further. Computational fluid dynamics dispenses with many of the simplifying assumptions used to derive classical formulas and computer software facilitates optimization. These tools have led to steady improvements in turbine design over the last forty years.

The primary numerical classification of a turbine is its ***specific speed***. This number describes the speed of the turbine at its maximum efficiency with respect to the power and flow rate. The specific speed is derived to be independent of turbine size. Given the fluid flow conditions and the desired shaft output speed, the specific speed can be calculated and an appropriate turbine design selected.

The specific speed, along with some fundamental formulas can be used to reliably scale an existing design of known performance to a new size with corresponding performance.

Off-design performance is normally displayed as a turbine map or characteristic.

Types of turbines

- Steam turbines are used for the generation of electricity in thermal power plants, such as plants using coal, fuel oil or nuclear power. They were once used to directly drive mechanical devices such as ships' propellors (eg the Turbinia), but most such applications now use reduction gears or an intermediate electrical step, where the turbine is used to generate electricity, which then powers an electric motor connected to the mechanical load. Turbo electric ship machinery was particularly popular in the period immediately before and during WWII, primarily due to a lack of sufficient gear-cutting facilities in US and UK shipyards.

- Gas turbines are sometimes referred to as turbine engines. Such engines usually feature an inlet, fan, compressor, combustor and nozzle (possibly other assemblies) in addition to one or more turbines.
- Transonic turbine. The gasflow in most turbines employed in gas turbine engines remains subsonic throughout the expansion process. In a transonic turbine the gasflow becomes supersonic as it exits the nozzle guide vanes, although the downstream velocities normally become subsonic. Transonic turbines operate at a higher pressure ratio than normal but are usually less efficient and uncommon.

- Contra-rotating turbines. With axial turbines, some efficiency advantage can be obtained if a downstream turbine rotates in the opposite direction to an upstream unit. However, the complication can be counter-productive. A contra-rotating steam turbine, usually known as the Ljungström turbine, was originally invented by Swedish Engineer Fredrik Ljungström (1875–1964), in Stockholm and in partnership with his brother Birger Ljungström he obtained a patent in 1894. The design is essentially a multi-stage radial turbine (or pair of 'nested' turbine rotors) offering great efficiency, four times as large heat drop per stage as in the reaction (Parsons) turbine, extremely compact design and the type met particular success in backpressure power plants. However, contrary to other designs, large steam volumes are handled with difficulty and only a combination with axial flow turbines (DUREX) admits the turbine to be built for power greater than ca 50 MW. In marine applications only about 50 turbo-electric units were ordered (of which a considerable amount were finally sold to land plants) during 1917-19, and during 1920-22 a few turbo-mechanic not very successful units were sold. Only a few turbo-electric marine plants were still in use in the late 1960s (ss Ragne, ss Regin) while most land plants remain in use 2010.

- Statorless turbine. Multi-stage turbines have a set of static (meaning stationary) inlet guide vanes that direct the gasflow onto the rotating rotor blades. In a statorless turbine the gasflow exiting an upstream rotor impinges onto a downstream rotor without an intermediate set of stator vanes (that rearrange the pressure/velocity energy levels of the flow) being encountered.

- Ceramic turbine. Conventional high-pressure turbine blades (and vanes) are made from nickel based alloys and often utilise intricate internal air-cooling passages to prevent the metal from overheating. In recent years, experimental ceramic blades have been manufactured and tested in gas turbines, with a view to increasing Rotor Inlet Temperatures and/or, possibly, eliminating aircooling. Ceramic blades are more brittle than their metallic counterparts, and carry a greater risk of catastrophic blade failure. This has tended to limit their use in jet engines and gas turbines, to the stator (stationary) blades.

- Shrouded turbine. Many turbine rotor blades have shrouding at the top, which interlocks with that of adjacent blades, to increase damping and thereby reduce blade flutter. In large land-based electricity generation steam turbines, the shrouding is often complemented, especially in the long blades of a low-pressure turbine, with lacing wires. These are wires which pass through holes drilled in the blades at suitable distances from the blade root and the wires are usually brazed to the blades at the point where they pass through. The lacing wires are designed to reduce blade flutter in the central part of the blades. The introduction of lacing wires substantially reduces the instances of blade failure in large or low-pressure turbines.

- Shroudless turbine. Modern practice is, wherever possible, to eliminate the rotor shrouding, thus reducing the centrifugal load on the blade and the cooling requirements.
- Bladeless turbine uses the boundary layer effect and not a fluid impinging upon the blades as in a conventional turbine.
- Water turbines
    - Pelton turbine, a type of impulse water turbine.
    - Francis turbine, a type of widely used water turbine.
    - Kaplan turbine, a variation of the Francis Turbine.
- Wind turbine. These normally operate as a single stage without nozzle and interstage guide vanes. An exception is the Éolienne Bollée, which has a stator and a rotor, thus being a true turbine.

Other

- Velocity compound "Curtis". Curtis combined the de Laval and Parsons turbine by using a set of fixed nozzles on the first stage or stator and then a rank of fixed and rotating blade rows, as in the Parsons or de Laval, typically up to ten compared with up to a hundred stages of a Parsons design. The overall efficiency of a Curtis design is less than that of either the Parsons or de Laval designs, but it can be satisfactorily operated through a much wider range of speeds, including successful operation at low speeds and at lower pressures, which made it ideal for use in ships' powerplant. In a Curtis arrangement, the entire heat drop in the steam takes place in the initial nozzle row and both the subsequent moving blade rows and stationary blade rows merely change the direction of the steam. Use of a small section of a Curtis arrangement, typically one nozzle section and two or three rows of moving blades, is usually termed a Curtis 'Wheel' and in this form, the Curtis found widespread use at sea as a 'governing stage' on many reaction and impulse turbines and turbine sets. This practice is still commonplace today in marine steam plant.

- Pressure Compound Multistage Impulse or Rateau. The Rateau employs simple Impulse rotors separated by a nozzle diaphragm. The diaphragm is essentially a partition wall in the turbine with a series of tunnels cut into it, funnel shaped with the broad end facing the previous stage and the narrow the next they are also angled to direct the steam jets onto the impulse rotor.

- Positive displacement hydraulic devices. In a turbine, the fluid's own pressure accelerates it and the momentum and kinetic energy of the moving fluid do the mechanical work. An alternative is the reverse of a positive displacement pump, in which the pressure of the fluid does work directly on moving surfaces. As with pumps such as superchargers, these devices tend to have much wider speed and pressure ranges than turbines do, but they are larger and less efficient at high power. These are common, for example, in the power steering of cars.

Uses of turbines

Almost all electrical power on Earth is produced with a turbine of some type. Very high efficiency steam turbines harness about 40% of the thermal energy, with the rest exhausted as waste heat.

Most jet engines rely on turbines to supply mechanical work from their working fluid and fuel as do all nuclear ships and power plants.

Turbines are often part of a larger machine. A gas turbine, for example, may refer to an internal combustion machine that contains a turbine, ducts, compressor, combustor, heat-exchanger, fan and (in the case of one designed to produce electricity) an alternator. Combustion turbines and steam turbines may be connected to machinery such as pumps and compressors, or may be used for propulsion of ships, usually through an intermediate gearbox to reduce rotary speed.

Reciprocating piston engines such as aircraft engines can use a turbine powered by their exhaust to drive an intake-air compressor, a configuration known as a turbocharger (turbine supercharger) or, colloquially, a "turbo".

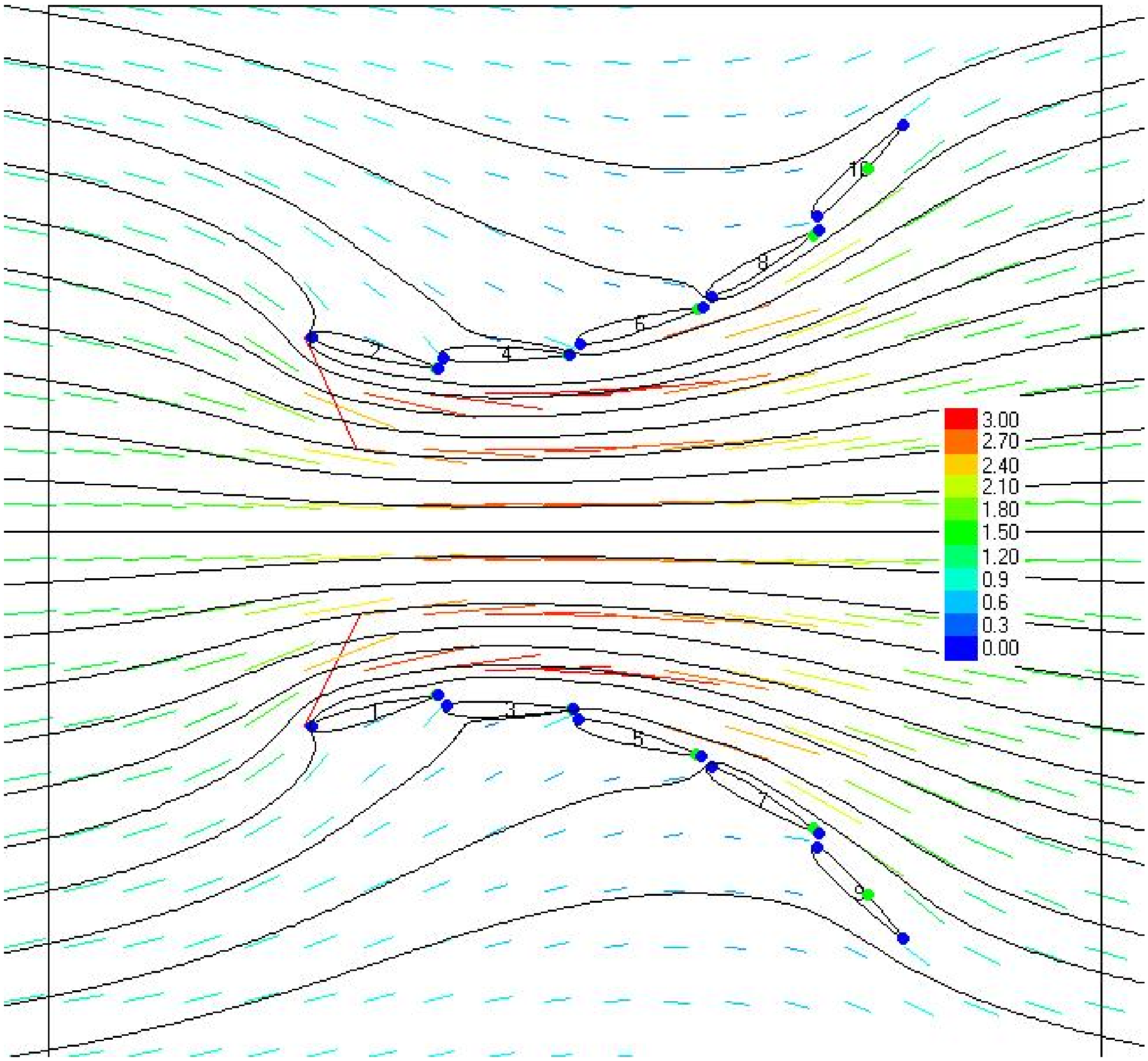
Turbines can have very high power density (ie the ratio of power to weight, or power to volume). This is because of their ability to operate at very high speeds. The Space Shuttle's main engines use turbopumps (machines consisting of a pump driven by a turbine engine) to feed the propellants (liquid oxygen and liquid hydrogen) into the engine's combustion chamber. The liquid hydrogen turbopump is slightly larger than an automobile engine (weighing approximately 700 lb) and produces nearly 70,000 hp (52.2 MW).

Turboexpanders are widely used as sources of refrigeration in industrial processes.

Shrouded tidal turbines

An emerging renewable energy technology is the shrouded tidal turbine enclosed in a venturi shaped shroud or duct producing a sub atmosphere of low pressure behind the turbine. It is often claimed that this allows the turbine to operate at higher efficiency (than the Betz limit of 59.3%) because the turbine can typically produce 3 times more power than a turbine of the same size in free stream. This, however, is something of a misconception because the area presented to the flow is that of the largest duct cross-section. If this area is used for the calculation, it will be seen that the turbine still cannot exceed the Betz limit. Further, due to frictional losses in the duct, it is unlikely that the turbine will be able to produce as much power as a free-stream turbine with the same radius as the duct.

Although situating the rotor in the throat of the duct allows the blades to be supported at their tips (thus reducing bending stress from hydrodynamic thrust) the financial impact of the large amount of steel in the duct must not be omitted from any energy cost calculations.



Asymmetric airfoil

As shown in the CFD generated figure, it can be seen that a down stream low pressure (shown by the gradient lines) draws upstream flow into the inlet of the shroud from well outside the inlet of the shroud. This flow is drawn into the shroud and concentrated (as seen by the red coloured zone). This augmentation of flow velocity corresponds to a 3-4 times increase in energy available to the turbine. Therefore a turbine located in the throat of the shroud is then able to achieve higher efficiency, and an output 3-4 times the energy the turbine would be capable of if it were in open or free stream. However, as mentioned above, it is not correct to conclude that this circumvents the Betz limit. The figure shows only the near-field flow, which is accelerated through the duct. A far-field image would show a more complete picture of how the free-stream flow is affected by the obstruction.

Considerable commercial interest has been shown in recent times in shrouded tidal turbines as it allows a smaller turbine to be used at sites where large turbines are restricted. Arrayed across a seaway or in fast flowing rivers shrouded tidal turbines are easily cabled to a terrestrial base and connected to a grid or remote community.

Alternatively the property of the shroud that produces an accelerated flow velocity across the turbine allows tidal flows formerly too slow for commercial use to be utilised for commercial energy production.

While the shroud may not be practical in wind, as a tidal turbine it is gaining more popularity and commercial use. A non-symmetrical shrouded tidal turbine (the type discussed above) is mono directional and constantly needs to face upstream in order to operate. It can be floated under a pontoon on a swing mooring, fixed to the seabed on a mono pile and yawed like a wind sock to continually face upstream. A shroud can also be built into a tidal fence increasing the performance of the turbines. Several companies (for example, Lunar Energy) are proposing bi-directional ducts that would not be required to turn to face the oncoming tide every six hours.

Cabled to the mainland they can be grid connected or can be scaled down to provide energy to remote communities where large civil infrastructures are not viable. Similarly to tidal stream open turbines they have little if any environmental or visual amenity impact.

Chapter 6

Wheel

Three wheels on an antique tricycle

A **wheel** is a device that allows heavy objects to be moved easily through rotating on an axle through its center, facilitating movement or transportation while supporting a load (mass), or performing labor in machines. Common examples found in transport applications. A wheel, together with an axle, overcomes friction by facilitating motion by rolling. In order for wheels to rotate, a moment needs to be applied to the wheel about its axis, either by way of gravity, or by application of another external force. More generally the term is also used for other circular objects that rotate or turn, such as a ship's wheel, steering wheel and flywheel.

Etymology

The English word *wheel* comes from the Old English word *hweol, hweogol*, from Proto-Germanic **hwehwlan, *hwegwlan*, from Proto-Indo-European **k^{w}ek^{w}lo-*, an extended form of the root **k^{w}el-* "to revolve, move around". Cognates within Indo-European include Greek κύκλος *kýklos*, "wheel", Sanskrit *chakra*, Old Church Slavonic *kolo*, all meaning "circle" or "wheel",

The Latin word *rota* is from the Proto-Indo-European **rotā-*, the extended o-grade form of the root **ret-* meaning "to roll, revolve".

History

Evidence of wheeled vehicles appears from the mid 4th millennium BCE, near-simultaneously in Mesopotamia, the Northern Caucasus (Maykop culture) and Central Europe, and so the question of which culture originally invented the wheeled vehicle remains unresolved and under debate.

The earliest well-dated depiction of a wheeled vehicle (here a wagon—four wheels, two axles), is on the Bronocice pot, a ca. 3500–3350 BCE clay pot excavated in a Funnelbeaker culture settlement in southern Poland.

The wheeled vehicle from the area of its first occurrence (Mesopotamia, Caucasus, Balkans, Central Europe) spread across Eurasia, reaching the Indus Valley by the 3rd millennium BCE. During the 2nd millennium BCE, the spoke-wheeled chariot spread at an increased pace, reaching both China and Scandinavia by 1200 BCE. In China, the wheel was certainly present with the adoption of the chariot in ca. 1200 BCE, although Barbieri-Low argues for earlier Chinese wheeled vehicles, circa 2000 BCE.

Although they did not develop the wheel proper, the Olmec and certain other western hemisphere cultures seem to have approached it, as wheel-like worked stones have been found on objects identified as children's toys dating to about 1500 BCE. Early antiquity Nubians used wheels for spinning pottery and waterwheels. It is thought that Nubian waterwheels may have been ox-driven It is also known that Nubians used horse-driven chariots imported from Egypt.

The invention of the wheel thus falls in the late Neolithic, and may be seen in conjunction with the other technological advances that gave rise to the early Bronze Age. Note that this implies the passage of several wheel-less millennia even after the invention of agriculture and of pottery:

- 9500–6500 BCE: Aceramic Neolithic

- 6500–4500 BCE: Ceramic Neolithic (Halafian)
- ca. 4500 BCE: invention of the potter's wheel, beginning of the Chalcolithic (Ubaid period)
- 4500–3300 BCE: Chalcolithic, earliest wheeled vehicles, domestication of the horse
- 3300–2200 BCE: Early Bronze Age
- 2200–1550 BCE: Middle Bronze Age, invention of the spoked wheel and the chariot

Wide usage of the wheel was probably delayed because smooth roads were needed for wheels to be effective. Carrying goods on the back would have been the preferred method of transportation over surfaces that contained many obstacles. The lack of developed roads prevented wide adoption of the wheel for transportation until well into the 20th century in less developed areas.

Early wheels were simple wooden disks with a hole for the axle. Because of the structure of wood a horizontal slice of a trunk is not suitable, as it does not have the structural strength to support weight without collapsing; rounded pieces of longitudinal boards are required. The oldest known example of a wooden wheel and its axle were found in 2003 at the Ljubljana Marshes some 20 km south of Ljubljana, the capital of Slovenia. According to the radiocarbon dating, it is between 5,100 and 5,350 years old.

The spoked wheel was invented more recently, and allowed the construction of lighter and swifter vehicles. The earliest known examples are in the context of the Andronovo culture, dating to ca 2000 BCE. Soon after this, horse cultures of the Caucasus region used horse-drawn spoked-wheel war chariots for the greater part of three centuries. They moved deep into the Greek peninsula where they joined with the existing Mediterranean peoples to give rise, eventually, to classical Greece after the breaking of Minoan dominance and consolidations led by pre-classical Sparta and Athens. Celtic chariots introduced an iron rim around the wheel in the 1st millennium BCE. The spoked wheel was in continued use without major modification until the 1870s, when wire wheels and pneumatic tires were invented.

The invention of the wheel has also been important for technology in general, important applications including the water wheel, the cogwheel, the spinning wheel, and the astrolabe or torquetum. More modern descendants of the wheel include the propeller, the jet engine, the flywheel (gyroscope) and the turbine.

Mechanics and function

The wheel is a device that enables efficient movement of an object across a surface where there is a force pressing the object to the surface. Common examples are a cart pulled by a horse, and the rollers on an aircraft flap mechanism.

Wheels are used in conjunction with axles, either the wheel turns on the axle, or the axle turns in the object body. The mechanics are the same in either case.

The low resistance to motion (compared to dragging) is explained as follows (refer to friction):

- the normal force at the sliding interface is the same.
- the sliding distance is reduced for a given distance of travel.
- the coefficient of friction at the interface is usually lower.

Bearings are used to help reduce friction at the interface. In the simplest and oldest case the bearing is just a round hole through which the axle passes (a "plain bearing").

Example:

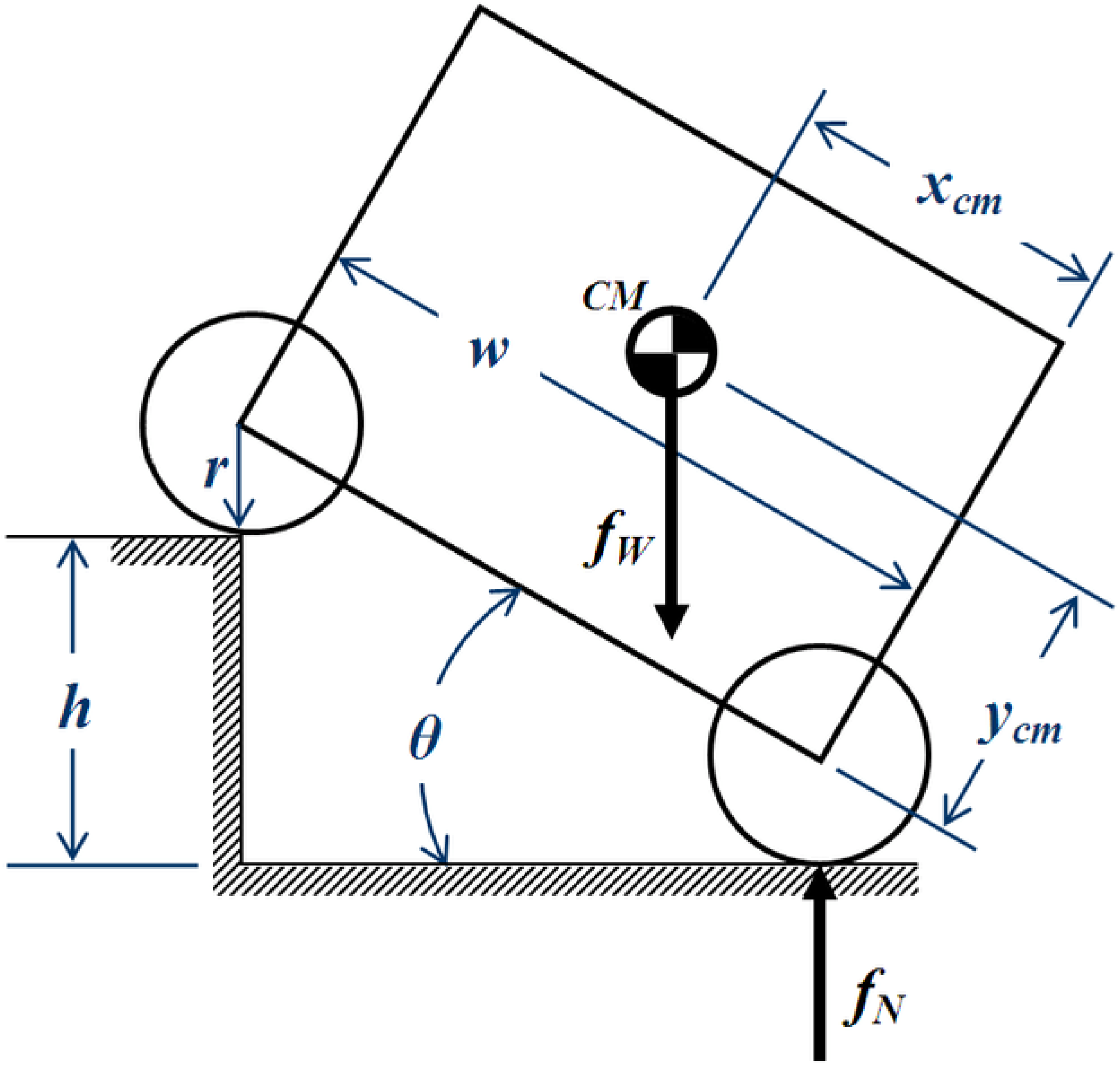
- If dragging a 100 kg object for 10 m along a surface with the coefficient of friction $\mu = 0.5$, the normal force is 981 N and the work done (required energy) is (work=force x distance) $981 \times 0.5 \times 10 = 4905$ joules.
- Now give the object 4 wheels. The normal force between the 4 wheels and axles is the same (in total) 981 N, assume, for wood, $\mu = 0.25$, and say the wheel diameter is 1000 mm and axle diameter is 50 mm. So while the object still moves 10 m the sliding frictional surfaces only slide over each other a distance of 0.5 m. The work done is $981 \times 0.25 \times 0.5 = 123$ joules; the friction is reduced to 1/40 of that of dragging.

Additional energy is lost from the wheel-to-road interface. This is termed rolling resistance which is predominantly a deformation loss.

A wheel can also offer advantages in traversing irregular surfaces if the wheel radius is sufficiently large compared to the irregularities.

The wheel alone is not a machine, but when attached to an axle in conjunction with bearing, it forms the wheel and axle, one of the simple machines. A driven wheel is an example of a wheel and axle. Note that wheels pre-date driven wheels by about 6000 years.

Stability



Static stability of a wheeled vehicle

For unarticulated wheels, climbing obstacles will cause the body of the vehicle to rotate. If the rotation angle is too high, the vehicle will become statically unstable and tip over. At high speeds, a vehicle can become dynamically unstable, able to be tipped over by an obstacle smaller than its static stability limit. Without articulation, this can be an impossible position from which to recover.

For front-to-back stability, the maximum height of an obstacle which an unarticulated wheeled vehicle can climb is a function of the wheelbase and the horizontal and vertical position of the center of mass (CM).

The *critical angle* is the angle at which the center of mass of the vehicle begins to pass outside of the contact points of the wheels. Past the critical angle, the reaction forces at the wheels can no longer counteract the moment created by the vehicle's weight, and the vehicle will tip over. At the critical angle, the vehicle is marginally stable. The critical angle θ_{crit} can be found by solving the equation:

$$\theta_{crit} = \tan^{-1}\left(\frac{x_{cm} + r\sin\theta_{crit}}{y_{cm} + r\sin\theta_{crit}}\right)$$

where

> r is the radius of the wheels;
> x_{cm} is the horizontal distance of the center of mass from the rear axle; and
> y_{cm} is the vertical distance of the center of mass from the axles.

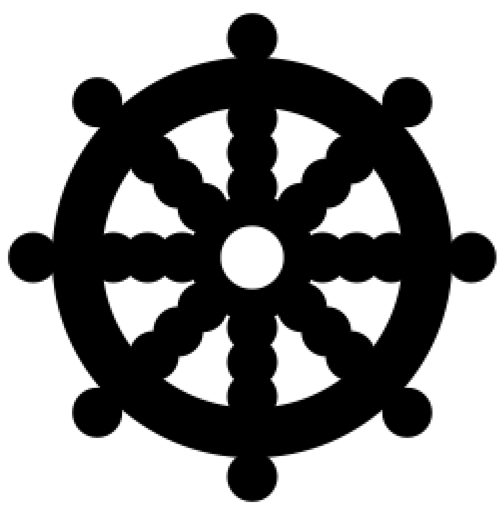
For small wheels, this formula can be simplified to:

$$\theta_{crit} = \tan^{-1}\left(\frac{x_{cm}}{y_{cm}}\right)$$

The maximum height h of an obstacle can be found by the equation:

$$h = w\sin\theta_{crit}$$

where w is the wheelbase.



In the Unicode computer standard, the Dharmacakra is called the "Wheel of Dharma" and found in the eight-spoked form. It is represented as U+2638 (☸)

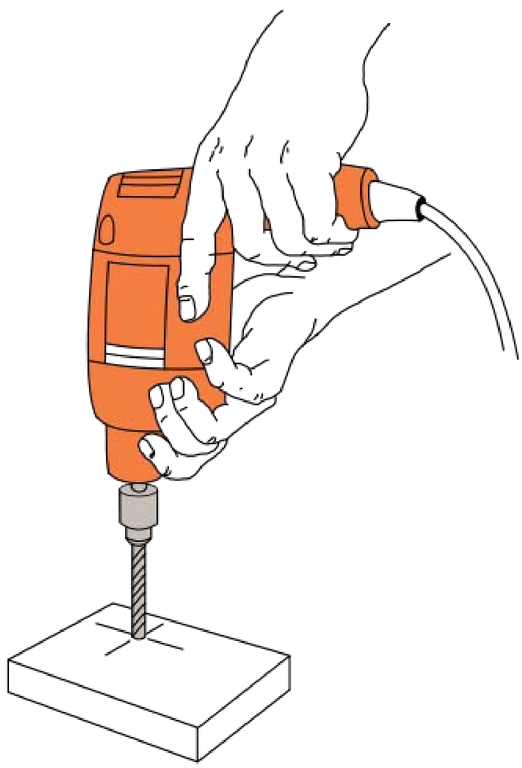
Alternatives

While wheels are used for ground transport very widely, there are alternatives, some of which are suitable for terrain where wheels are ineffective. Alternative methods for ground transport without wheels (wheel-less transport) include:

- Being raised by electromagnetic energy (maglev train and other vehicles)
- Dragging with runners (sled) or without (travois)
- Being raised by air pressure (hovercraft)
- Riding an animal such as a horse
- Human powered:
    - Walking on one's own legs
    - Being carried (litter/sedan chair or stretcher)
- A walking machine
- Caterpillar tracks (although it is still operated by wheels)
- Spheres, as used by Dyson vacuum cleaners and hamster balls

Chapter 7

Drill



Drill scheme

A **drill** or **drill motor** is a tool fitted with a cutting tool attachment or driving tool attachment, usually a drill bit or driver bit, used for drilling holes in various materials or fastening various materials together with the use of fasteners. The attachment is gripped by a chuck at one end of the drill and rotated while pressed against the target material. The tip, and sometimes edges, of the cutting tool does the work of cutting into the target material. This may be slicing off thin shavings (twist drills or auger bits), grinding off small particles (oil drilling), crushing and removing pieces of the workpiece (SDS masonry drill), countersinking, counterboring, or other operations.

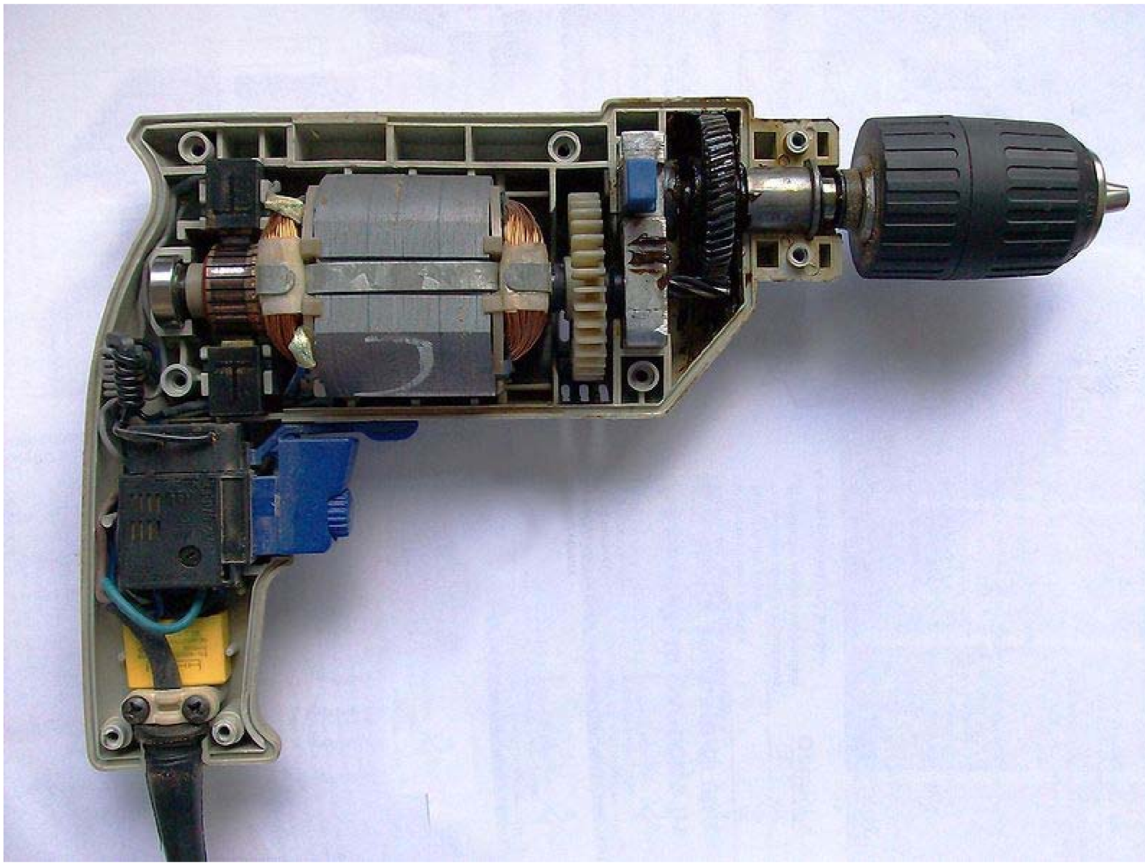
Drills are commonly used in woodworking, metalworking, construction and do-it-yourself projects. Specially designed drills are also used in medicine, space missions and other applications.

History

A wooden drill handle and other carpentry tools found on board the 16th century carrack *Mary Rose*.

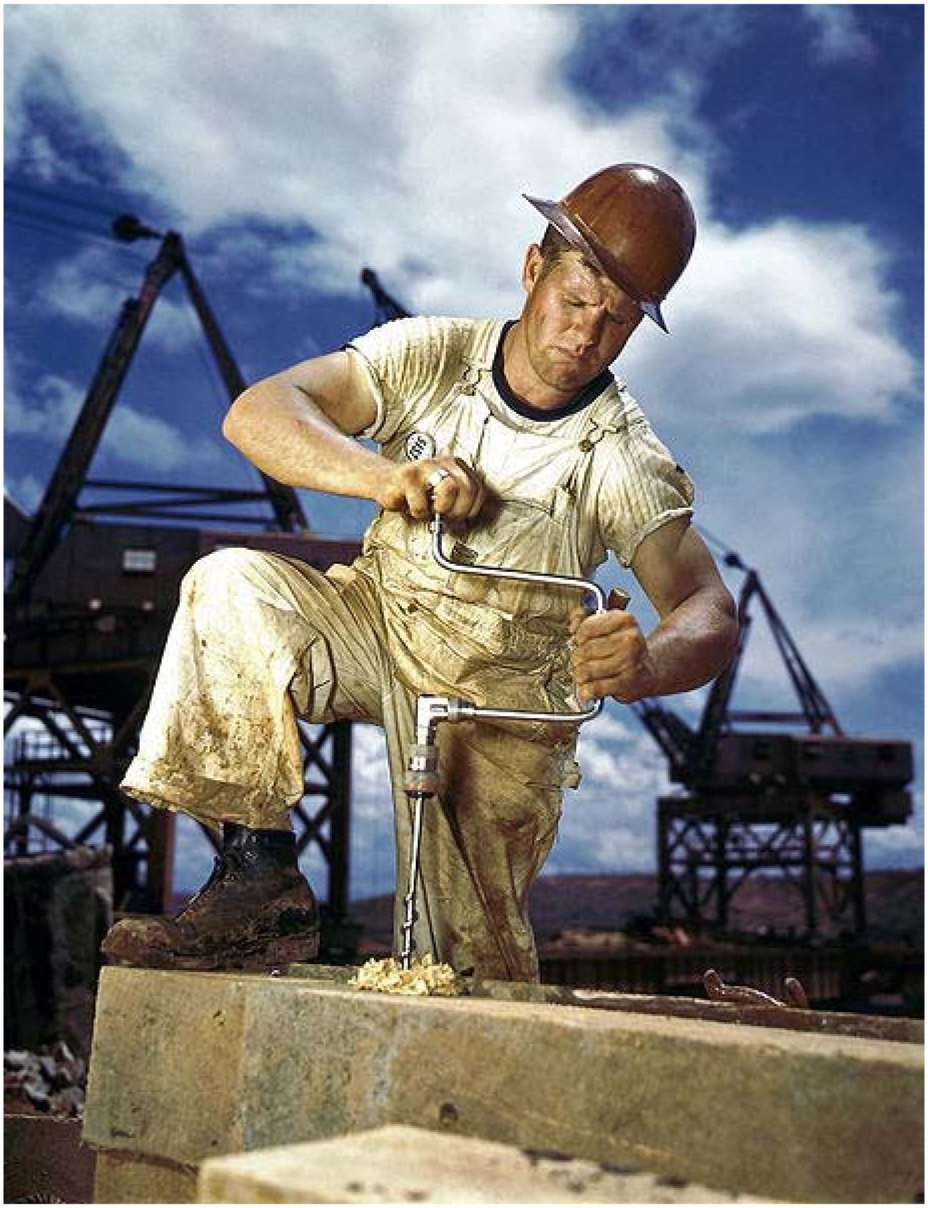
The earliest drills were bow drills which date back to the ancient Harappans and Egyptians. The drill press as a machine tool evolved from the bow drill and is many centuries old. It was powered by various power sources over the centuries, such as human effort, water wheels, and windmills, often with the use of belts. With the coming of the electric motor in the late 19th century, there was a great rush to power machine tools with such motors, and drills were among them. The invention of the first electric drill is credited to Arthur James Arnot and William Blanch Brain , in 1889, at Melbourne, Australia. Wilhelm Fein invented the portable electric drill in 1895, at Stuttgart, Germany. In 1917, Black & Decker patented a trigger-like switch mounted on a pistol-grip handle.

Types



Inside an electric drill

There are many types of drills: some are powered manually, others use electricity (electric drill) or compressed air (*pneumatic drill*) as the motive power, and a minority are driven by an internal combustion engine (for example, earth drilling augers). Drills with a percussive action (hammer drills) are mostly used in hard materials such as masonry (brick, concrete and stone) or rock. Drilling rigs are used to bore holes in the earth to obtain water or oil. Oil wells, water wells, or holes for geothermal heating are created with large drilling rigs. Some types of hand-held drills are also used to drive screws and other fasteners. Some small appliances that have no motor of their own may be drill-powered, such as small pumps, grinders, etc.



Carpenter using a crank-powered brace to drill a hole

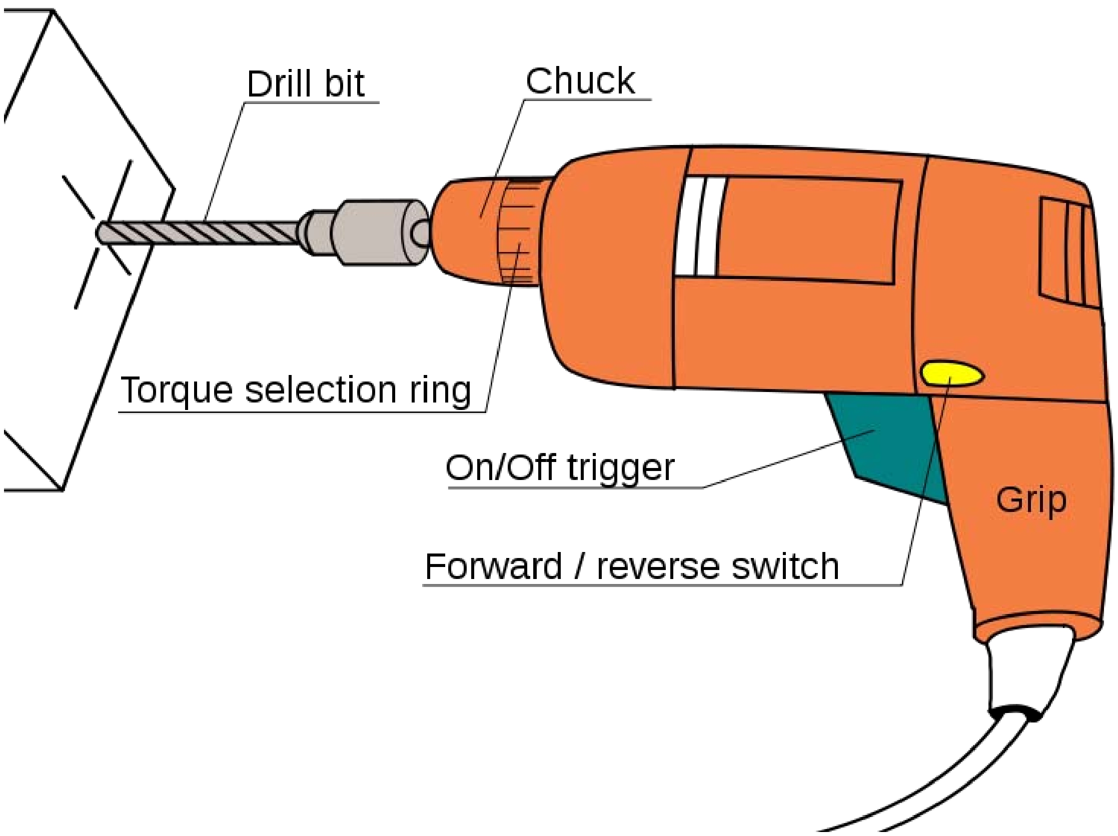
Hand tools

A variety of hand-powered drills have been employed over the centuries. Here are a few, starting with approximately the oldest:

- Bow drill
- Brace and bit
- Gimlet
- Breast drill, also known as "eggbeater" drill
- Push drill, a tool using a spiral ratchet mechanism
- Pin chuck, a small hand-held jewellers drill

An old hand drill or "eggbeater" drill. The hollow wooden handle, with screw-on cap, is used to store drill bits

Pistol-grip (corded) drill



Anatomy of a pistol-grip corded drill.

Drills with pistol grips are the most common type in use today, and are available in a huge variety of subtypes. A less common type is the right-angle drill, a special tool used by tradesmen such as plumbers and electricians.

For much of the 20th century, many attachments could commonly be purchased to convert corded electric hand drills into a range of other power tools, such as orbital sanders and power saws, more cheaply than purchasing conventional, self-contained versions of those tools (the greatest saving being the lack of an additional electric motor for each device). As the prices of power tools and suitable electric motors have fallen, however, such attachments have become much less common. A similar practice is currently employed for cordless tools where the battery, the most expensive component, is shared between various motorised devices, as opposed to a single electric motor being shared between mechanical attachments.

Hammer drill

The **hammer drill** is similar to a standard electric drill, with the exception that it is provided with a hammer action for drilling masonry. The hammer action may be engaged or disengaged as required. Most electric hammer drills are rated (input power) at between 600 and 1100 watts. The efficiency is usually 50-60% i.e. 1000 watts of input is converted into 500-600 watts of output (rotation of the drill and hammering action).

The hammer action is provided by two cam plates that make the chuck rapidly pulse forward and backward as the drill spins on its axis. This pulsing (hammering) action is measured in Blows Per Minute (BPM) with 10,000 or more BPMs being common. Because the combined mass of the chuck and bit is comparable to that of the body of the drill, the energy transfer is inefficient and can sometimes make it difficult for larger bits to penetrate harder materials such as poured concrete. The operator experiences considerable vibration, and the cams are generally made from hardened steel to avoid them wearing out quickly. In practice, drills are restricted to standard masonry bits up to 13 mm (1/2 inch) in diameter. A typical application for a hammer drill is installing electrical boxes, conduit straps or shelves in concrete.

In contrast to the cam-type hammer drill, a rotary/pneumatic hammer drill accelerates only the bit. This is accomplished through a piston design, rather than a spinning cam. Rotary hammers have much less vibration and penetrate most building materials. They can also be used as "drill only" or as "hammer only" which extends their usefulness for tasks such as chipping brick or concrete. Hole drilling progress is greatly superior to cam-type hammer drills, and these drills are generally used for holes of 19 mm (3/4 inch) or greater in size. A typical application for a rotary hammer drill is boring large holes for lag bolts in foundations, or installing large lead anchors in concrete for handrails or benches.

A standard hammer drill accepts 6 mm (1/4 inch) and 13 mm (1/2 inch) drill bits, while a rotary hammer uses SDS or Spline Shank bits. These heavy bits are adept at pulverising the masonry and drill into this hard material with relative ease.

However, there is a big difference in cost. In the UK a cam hammer typically costs £12 or more, while a rotary/pneumatic costs £35 or more. In the US a typical hammer drill costs between \$70 and \$120, and a rotary hammer between \$150 and \$500 (depending on bit size). For DIY use or to drill holes less than 13 mm (1/2 inch) in size, the hammer drill is most commonly used.

Rotary hammer drill

A rotary hammer drill used in construction

The rotary hammer drill (also known as a rotary hammer, roto hammer drill or masonry drill) combines a primary dedicated hammer mechanism with a separate rotation mechanism, and is used for more substantial material such as masonry or concrete. Generally, standard chucks and drills are inadequate and chucks such as SDS and carbide drills that have been designed to withstand the percussive forces are used. Some styles of this tool are intended for masonry drilling only and the hammer action cannot be disengaged. Other styles allow the drill to be used without the hammer action for normal drilling, or hammering to be used without rotation for chiselling.

Cordless drills

A cordless drill with clutch

A cordless drill is an electric drill which uses rechargeable batteries. These drills are available with similar features to an AC mains-powered drill. They are available in the hammer drill configuration and most have a clutch, which aids in driving screws into various substrates while not damaging them. Also available are right angle drills, which allow a worker to drive screws in a tight space. While 21st century battery innovations allow significantly more drilling, large diameter holes (typically 12–25 mm (0.5–1.0 in) or larger) may drain current cordless drills quickly.

For continuous use, a worker will have one or more spare battery packs charging while drilling, and quickly swap them instead of having to wait an hour or more for recharging, although there are now Rapid Charge Batteries that can charge in 10–15 minutes.

Early cordless drills used interchangeable 7.2 V battery packs, and over the years available battery voltages have increased, with 18 V drills being most common, and higher voltage drills, such as 24V, 28V, and 36V, are made also. This allows these tools to produce as much torque as some mains-powered drills. The drawback of most current models is the use of nickel-cadmium (NiCd) batteries, which have limited life, self-discharging and eventually internally short circuiting due to dendrite growth. This severely limits battery life, and poses a hazardous materials disposal problem.

Lithium ion batteries are becoming more common because of their short charging time, longer life, and low weight. Instead of charging a tool for an hour to get 20 minutes of use, 20 minutes of charge can run the tool for an hour. Lithium-ion batteries also have a constant discharge rate. The power output remains constant until the battery is depleted, something that nickel-cadmium batteries also lack, and which makes the tool much more versatile. Lithium-ion batteries also hold a charge for a significantly longer time than nickel-cadmium batteries, about two years if not used, vs. 1 to 4 months for a nickel-cadmium battery. There are three major drawbacks to Lithium Ion batteries. 1. They do not perform well in low temperatures 2. The batteries are very expensive to replace. 3. The overall batteries can only handle about 1/3 of the recharges over a lifetime as a NiCad or NiMH battery. NiCad batteries can also be rebuilt or upgraded, diminishing the benefits of Li-ion batteries.

A cordless drill with a high torque (in excess of 30 Nm) works well as a screw driver even if working on a hardwood. In drilling the high torque is needed when the diameter of the drill is large.

The handles of cordless drills are usually made from polyurethane which is easy and quick to mold to a comfortable shape for holding. The main body of the drill is usually made from polyethylene as it is able to withstand the high temperatures which the drill reaches.

Drill press

A drill press

A drill press (also known as pedestal drill, pillar drill, or bench drill) is a fixed style of drill that may be mounted on a stand or bolted to the floor or workbench. A drill press consists of a base, column (or pillar), table, spindle (or quill), and drill head, usually driven by an induction motor. The head has a set of handles (usually 3) radiating from a central hub that, when turned, move the spindle and chuck vertically, parallel to the axis of the column. The table can be adjusted vertically and is generally moved by a rack and pinion; however, some older models rely on the operator to lift and reclamp the table in position. The table may also be offset from the spindle's axis and in some cases rotated to a position perpendicular to the column. The size of a drill press is typically measured in terms of *swing*. Swing is defined as twice the *throat distance*, which is the distance from the center of the spindle to the closest edge of the pillar. For example, a 16-inch (410 mm) drill press will have an 8-inch (200 mm) throat distance.

Old industrial drill press designed to be driven from the power source by a flat belt

A drill press has a number of advantages over a hand-held drill:

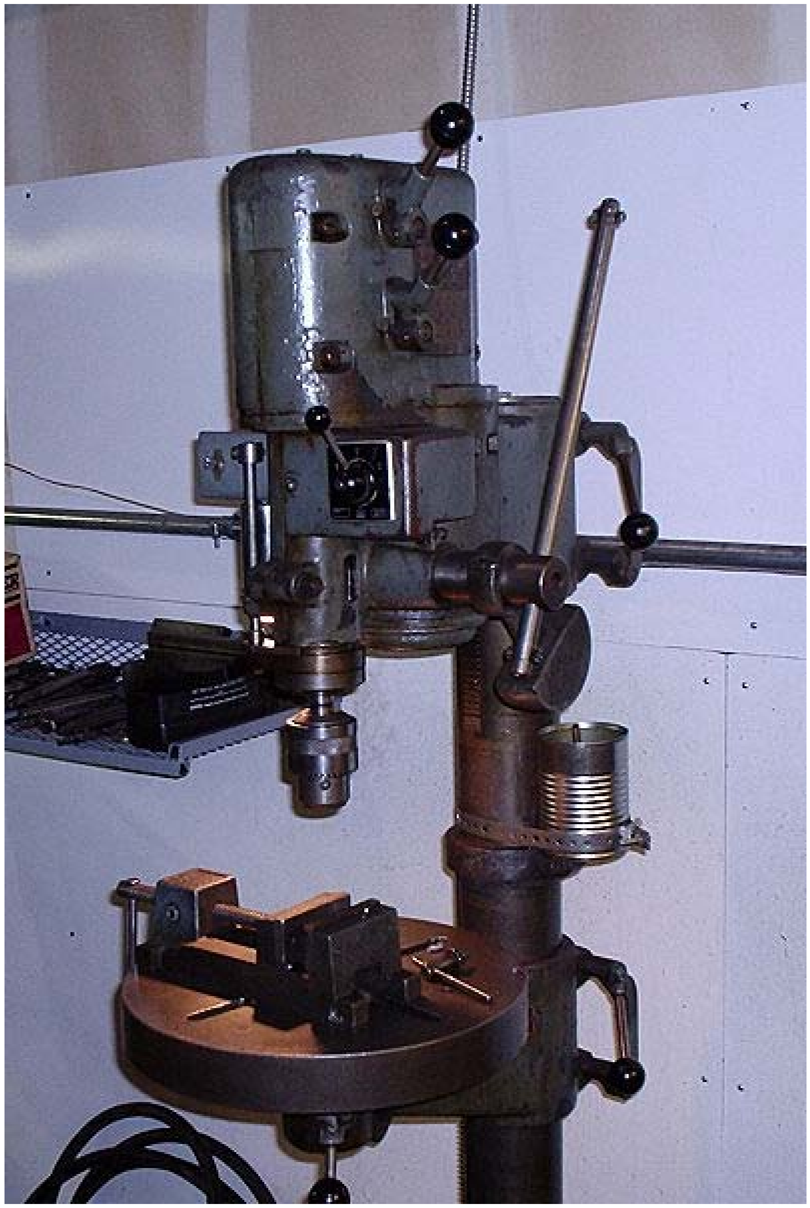
- Less effort is required to apply the drill to the workpiece. The movement of the chuck and spindle is by a lever working on a rack and pinion, which gives the operator considerable mechanical advantage
- The table allows a vise or clamp to be used to position and restrain the work, making the operation much more secure
- The angle of the spindle is fixed relative to the table, allowing holes to be drilled accurately and consistently

- Drill presses are almost always equipped with more powerful motors compared to hand-held drills. This enables larger drill bits to be used and also speeds up drilling with smaller bits.

Speed change is achieved by manually moving a belt across a stepped pulley arrangement. Some drill presses add a third stepped pulley to increase the speed range. Modern drill presses can, however, use a variable-speed motor in conjunction with the stepped-pulley system. Some machine shop (tool room) drill presses are equipped with a continuously variable transmission, giving a wide speed range, as well as the ability to change speed while the machine is running.

Drill presses are often used for miscellaneous workshop tasks such as sanding, honing or polishing, by mounting sanding drums, honing wheels and various other rotating accessories in the chuck. This can be unsafe in some cases, as the chuck arbor, which may be retained in the spindle solely by the friction of a taper fit, may dislodge during operation.

Geared head drill press

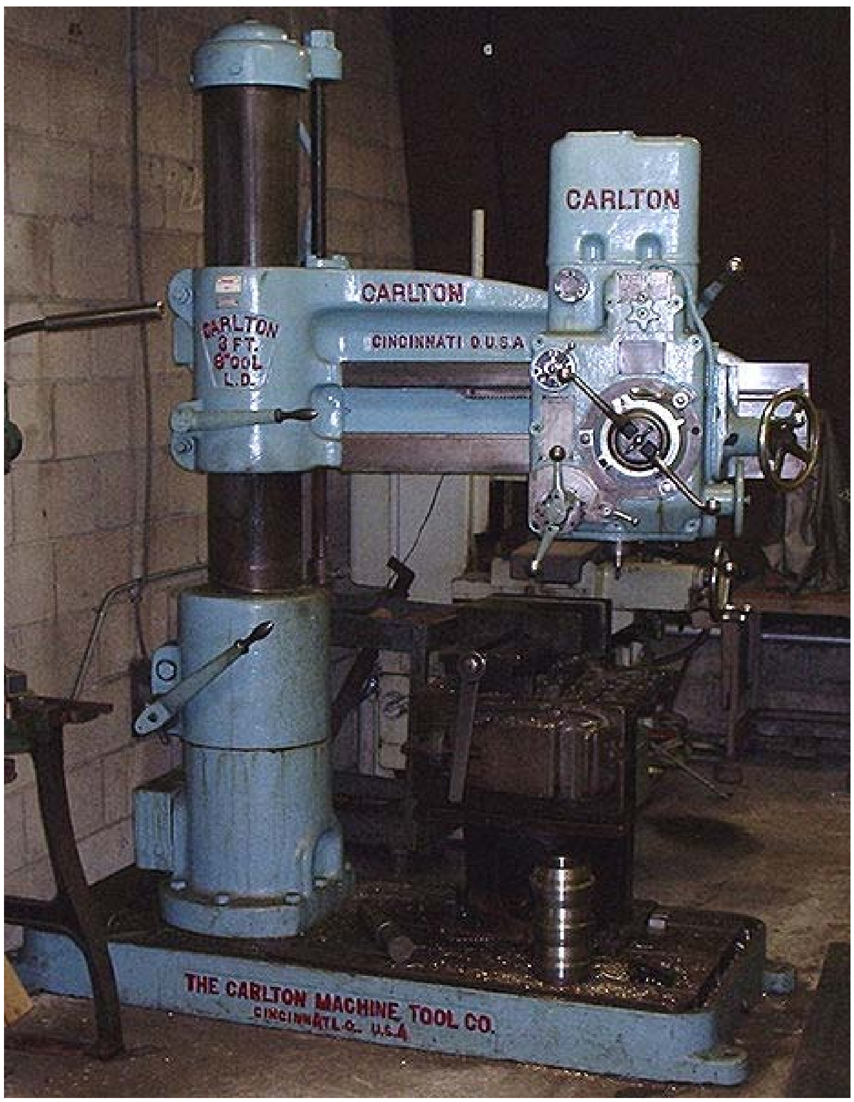


Geared head drill press. Shift levers on the head and a two speed motor control immediately in front of the quill handle select one of eight possible speeds

A geared head drill press is a drill press in which power transmission from the motor to the spindle is achieved solely through spur gearing inside the machine's head. No friction elements (e.g., belts) of any kind are used, which assures a positive drive at all times and minimizes maintenance requirements.

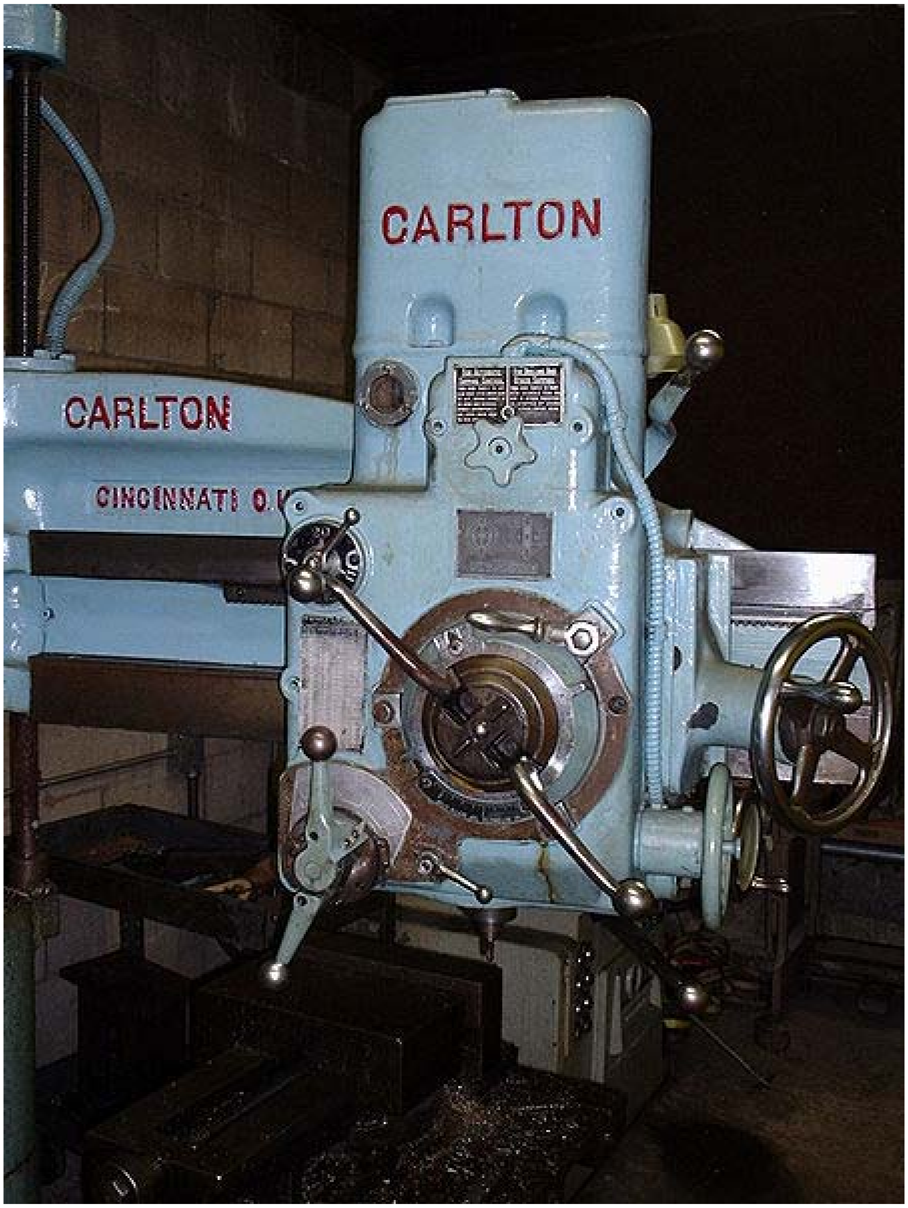
Levers attached to one side of the head are used to select different gear ratios to change the spindle speed, usually in conjunction with a two- or three-speed motor. Most machines of this type are designed to be operated on three phase power and are generally of more rugged construction than equivalent sized belt-driven units. Virtually all examples have geared racks for adjusting the table and head position on the column.

Geared head drill presses are commonly found in tool rooms and other commercial environments where a heavy duty machine capable of production drilling and quick setup changes is required. In most cases, the spindle is machined to accept Morse taper tooling for greater flexibility. Larger geared head drill presses are frequently fitted with power feed on the quill mechanism, with an arrangement to disengage the feed when a certain drill depth has been achieved or in the event of excessive travel. Some gear-head drill presses have the ability to perform tapping operations--a reversing mechanism drives the tap into the part under power and then backs it out of the threaded hole once the proper depth is reached. Coolant systems are also common on these machines to prolong tool life under production conditions.



Radial arm drill press.

Radial arm drill press



Radial arm drill press controls

A radial arm drill press is a large geared head drill press in which the head can be moved along an arm that radiates from the machine's column. As it is possible to swing the arm relative to the machine's base, a radial arm drill press is able to operate over a large area without having to reposition the workpiece. The size of work that can be handled may be considerable, as the arm can swing out of the way of the table, allowing an overhead crane or derrick to place a bulky piece on the table or base. A vise may be used with a radial arm drill press, but more often the workpiece is secured directly to the table or base, or is held in a fixture. Power spindle feed is nearly universal with these machines and coolant systems are common. The biggest radial arm drill presses are able to drill holes as large as four inches (101.6 millimeters) diameter in solid steel or cast iron.

Mill drill

Mill drills are a lighter alternative to a milling machine. They combine a drill press (belt driven) with the X/Y coordinate abilities of the milling machine's table and a locking collet that ensures that the cutting tool will not fall from the spindle when lateral forces are experienced against the bit. Although they are light in construction, they have the advantages of being space-saving and versatile as well as inexpensive, being suitable for light machining that may otherwise not be affordable.

Unusual Uses

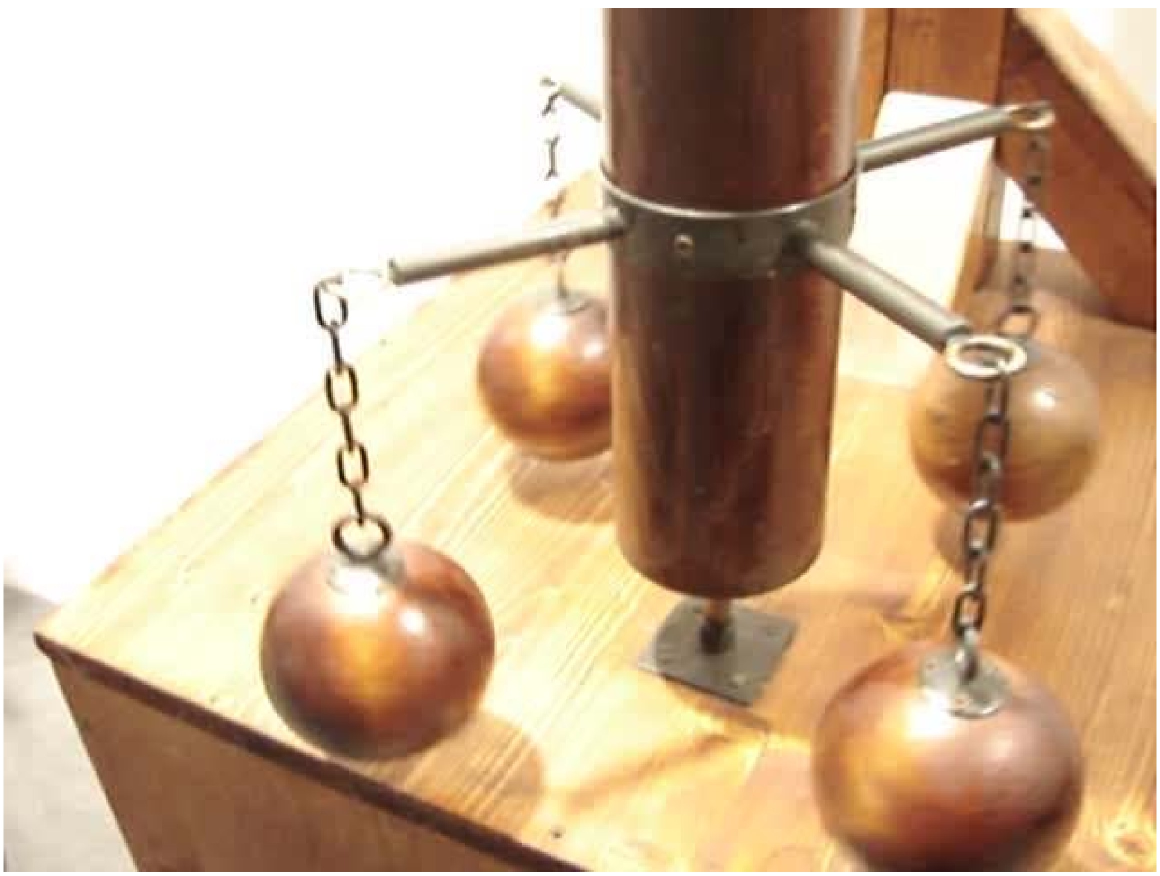
- A household drill was used to save a boy's life in Australia. The boy suffered from potentially fatal bleeding within the brain after a fall from his bike. Having no proper medical tools, the attending doctor decided to use a household drill stored in the hospital maintenance room to remove a clot. This was done in order to relieve the blood pressure in the boy's brain. If this had not been done, the boy would have died in minutes. The doctor performed the procedure and was guided by a neurosurgeon over the phone. The boy was later airlifted to a larger hospital and recovered within days.
- Paul Gilbert and Billy Sheehan of Mr. Big use a cordless drill for the solo of Daddy, Brother, Lover, Little Boy commonly known as "The Electric Drill Song". This was done by using 3.3mm plectrums on a wooden dowel.

Other perforation tools

- Milling machines, metal lathes and routers are also often used for drilling.

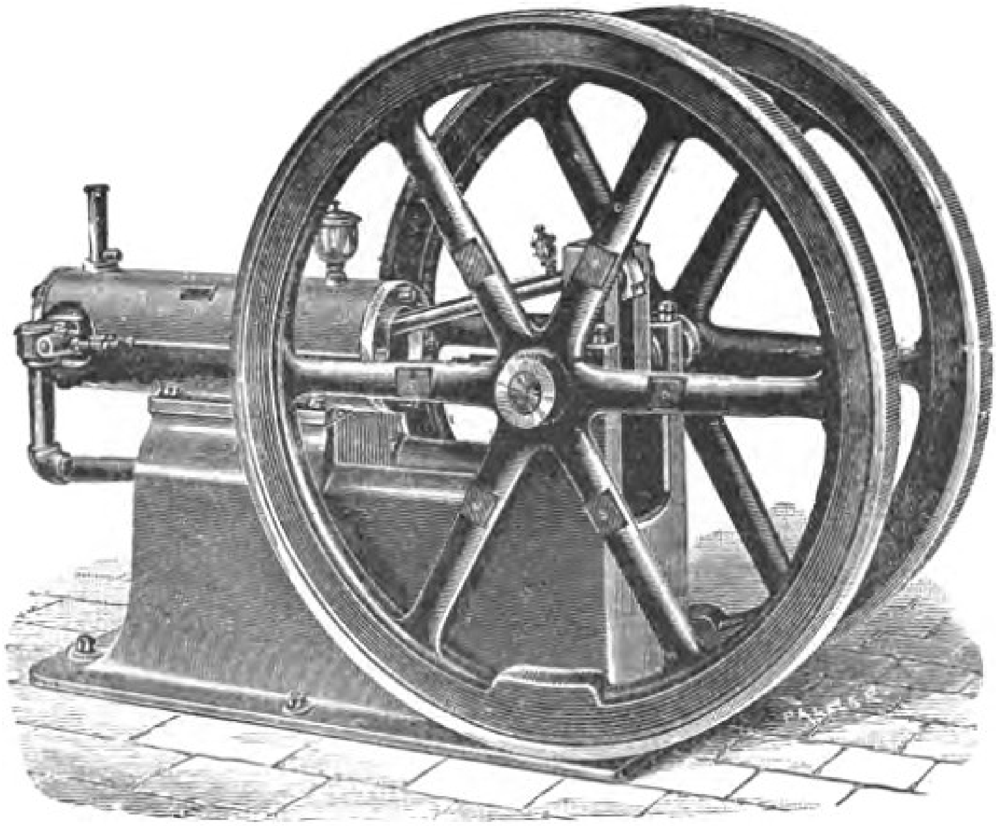
Chapter 8

Flywheel



Flywheel that keeps its rotation rate higher than in a rigid design, constructed based on drawings by Leonardo da Vinci

Flywheel from stationary engine. Note the castellated rim which was used to rotate the engine to the correct starting position by means of a lever



1898 illustration of a White and Middleton stationary engine; note the large twin flywheels

A Landini tractor with massive flywheel

1928 Lanz Bulldog showing the flywheels and a hot bulb engine

Zaschka helicopter with flywheels, Berlin Tempelhof Airport, 1930

Spoked flywheel

A **flywheel** is a mechanical device with a significant moment of inertia used as a storage device for rotational energy. Flywheels resist changes in their rotational speed, which helps steady the rotation of the shaft when a fluctuating torque is exerted on it by its power source such as that caused by a piston-based (reciprocating) engine, or when an intermittent load, such as the motion of a piston pump, is placed on it.

Flywheels can be used to produce very high power pulses for experiments, where drawing the power from the public network would produce unacceptable spikes. A small motor can accelerate the flywheel between the pulses.

Recently, flywheels have become the subject of extensive research as power storage devices for uses in vehicles and power plants.

History

The principle of the flywheel is found in the Neolithic spindle and the potter's wheel.

The Andalusian agronomist Ibn Bassal (fl 1038–1075), in his *Kitab al-Filaha*, describes the flywheel effect employed in a water wheel machine, the *saqiya*.

The flywheel as a general mechanical device for equalizing the speed of rotation is, according to the American medievalist Lynn White, recorded in the *De diversibus artibus* (On various arts) of the German artisan Theophilus Presbyter (ca. 1070–1125) who records applying the device in several of his machines.

In the Industrial Revolution, James Watt contributed to the development of the flywheel in the steam engine, and his contemporary James Pickard used a flywheel combined with a crank to transform reciprocating into rotary motion.

Physics

A flywheel is a spinning wheel or disc with a fixed axle so that rotation is only about one axis. Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

- $E_k = \frac{1}{2} I \omega^2$

Where:

- ω is the angular velocity, and
- *I* is the moment of inertia of the mass about the center of rotation. The moment of inertia is the measure of resistance to torque applied on a spinning object (i.e. the higher the moment of inertia, the slower it will spin after being applied a given force).

- The moment of inertia for a solid-cylinder is $I_z = \frac{1}{2}mr^2$,
- for a thin-walled empty cylinder is $I = mr^2$,
- and for a thick-walled empty cylinder is $I = \frac{1}{2}m({r_{external}}^2 + {r_{internal}}^2)$,

Where *m* denotes mass, and *r* denotes a radius.

When calculating with SI units, the standards would be for mass, kilograms; for radius, meters; and for angular velocity, radians per second. The resulting answer would be in joules.

The amount of energy that can safely be stored in the rotor depends on the point at which the rotor will warp or shatter. The hoop stress on the rotor is a major consideration in the design of a flywheel energy storage system.

- $\sigma_t = \rho r^2 \omega^2$

Where:

- σ_t is the tensile stress on the rim of the cylinder
- ρ is the density of the cylinder
- *r* is the radius of the cylinder, and
- ω is the angular velocity of the cylinder.

Examples of energy stored

object	k (varies with shape)	mass	diameter	angular velocity	energy stored, [J]	energy stored, [Wh]
bicycle wheel at 20 km/h	1	1 kg	700 mm	150 rpm	15 J	4×10^{-3} Wh
bicycle wheel, double speed (40 km/h)	1	1 kg	700 mm	300 rpm	60 J	16×10^{-3} Wh

bicycle wheel, double mass (20 km/h)	1	2 kg	700 mm	150 rpm	30 J	8×10^{-3} Wh
Millstone grinding wheel	1/2	245 kg	500 mm	200 rpm	1.68 kJ	0.47 Wh
wheel on train @ 60 km/h	1/2	942 kg	1 m	318 rpm	65 kJ	18 Wh
giant dump truck wheel @ 30 km/h (18 mph)	1/2	1000 kg	2 m	79 rpm	17 kJ	4.8 Wh
small flywheel battery	1/2	100 kg	600 mm	20000 rpm	9.8 MJ	2.7 kWh
regenerative braking flywheel for trains	1/2	3000 kg	500 mm	8000 rpm	33 MJ	9.1 kWh
electrical power backup flywheel	1/2	600 kg	500 mm	30000 rpm	92 MJ	26 kWh
the planet Earth , Rotational energy	2/5	5.97×10^{27} g	12,725 km	~1 per day (696 µrpm)	2.6×10^{29} J	72 YWh ($\times 10^{24}$ Wh)

High-energy materials

For a given flywheel design, the kinetic energy is proportional to the ratio of the hoop stress to the material density and to the mass:

- $$E_k \propto \frac{\sigma_t}{\rho} m$$

$\frac{\sigma_t}{\rho}$ could be called the specific tensile strength. The flywheel material with the highest specific tensile strength will yield the highest energy storage per unit mass. This is one reason why carbon fiber is a material of interest.

For a given design the stored energy is proportional to the hoop stress and the volume:

- $E_k \propto \sigma_t V$

Applications

The phenomenon of precession has to be considered when using flywheels in vehicles. A rotating flywheel responds to any momentum that tends to change the direction of its axis of rotation by a resulting precession rotation. A vehicle with a vertical-axis flywheel would experience a lateral momentum when passing the top of a hill or the bottom of a valley (roll momentum in response to a pitch change). Two counter-rotating flywheels may be needed to eliminate this effect.

In a modern application, a momentum wheel is a type of flywheel useful in satellite pointing operations, in which the flywheels are used to point the satellite's instruments in the correct directions without the use of thruster rockets.

Flywheels are used in punching machines and riveting machines, where they store energy from the motor and release it during the operation cycle (punching and riveting).

For internal combustion engine applications, the flywheel is a heavy wheel mounted on the crankshaft. The main function of a flywheel is to maintain a constant angular velocity of the crankshaft.

Chapter 9

Centrifuge

A laboratory tabletop centrifuge.

A **centrifuge** is a piece of equipment, generally driven by an electric motor (some older models were spun by hand), that puts an object in rotation around a fixed axis, applying a force perpendicular to the axis. The centrifuge works using the sedimentation principle, where the centripetal acceleration causes more dense substances to separate out along the radial direction (the bottom of the tube). By the same token, lighter objects will tend to move to the top (of the tube; in the rotating picture, move to the centre).

In the picture shown, the rotating unit, called the rotor, has fixed holes drilled at an angle (to the vertical). Test tubes are placed in these slots and the rotor is spun. As the centrifugal force is in the horizontal plane and the tubes are fixed at an angle, the particles have to travel only a little distance before they hit the wall and drop down to the bottom. These angle rotors are very popular in the lab for routine use.

Theory

Protocols for centrifugation typically specify the amount of acceleration to be applied to the sample, rather than specifying a rotational speed such as revolutions per minute. This distinction is important because two rotors with different diameters running at the same rotational speed will subject samples to different accelerations. During circular motion the acceleration is the product of the radius and the square of the angular velocity and it is traditionally named "relative centrifugal force" (RCF). The acceleration is measured in multiples of "*g*" (or × "*g*"), the standard acceleration due to gravity at the Earth's surface, a dimensionless quantity given by the expression:

$$\mathrm{RCF} = \frac{r(2\pi N)^2}{g}$$

where

g is earth's gravitational acceleration,
r is the rotational radius,
N is the rotational speed, measured in revolutions per unit of time.

This relationship may be written as

$$\mathrm{RCF} = 1.118 \times 10^{-5}\, r_{\mathrm{cm}}\, N_{\mathrm{RPM}}^2$$

where

r_{cm} is the rotational radius measured in centimetres (cm),
N_{RPM} is rotational speed measured in revolutions per minute (RPM), and
$g = (980.65\ \mathrm{cm/sec^2})(3600\ \mathrm{sec^2/minute^2}) = 3,530,340\ \mathrm{cm/minute^2}$
.

History and predecessors

A 19th-century hand cranked laboratory centrifuge.

English military engineer Benjamin Robins (1707–1751) invented a whirling arm apparatus to determine drag. In 1864, Antonin Prandtl invented the first dairy centrifuge in order to separate cream from milk. In 1879, Gustaf de Laval demonstrated the first continuous centrifugal separator, making its commercial application feasible.

Types

There are at least five types of centrifuge:

- preparative centrifuge
- analytical centrifuge
- angle fixed centrifuge
- swing head centrifuge
- haematocrit centrifuge
- continuous tubular centrifuge

Industrial centrifuges may otherwise be classified according to the type of separation of the high density fraction from the low density one :

- Screen centrifuges, where the centrifugal acceleration allows the liquid to pass through a screen of some sort, through which the solids cannot go (due to granulometry larger than the screen gap or due to agglomeration). Common types are :
    - Pusher centrifuges
    - Peeler centrifuges
    - Decanter centrifuges, in which there is no physical separation between the solid and liquid phase, rather an accelerated settling due to centrifugal acceleration.
    - Continuous liquid

Common types are :

-
    - Solid bowl centrifuges
    - Conical plate centrifuges

Uses

Isolating suspensions

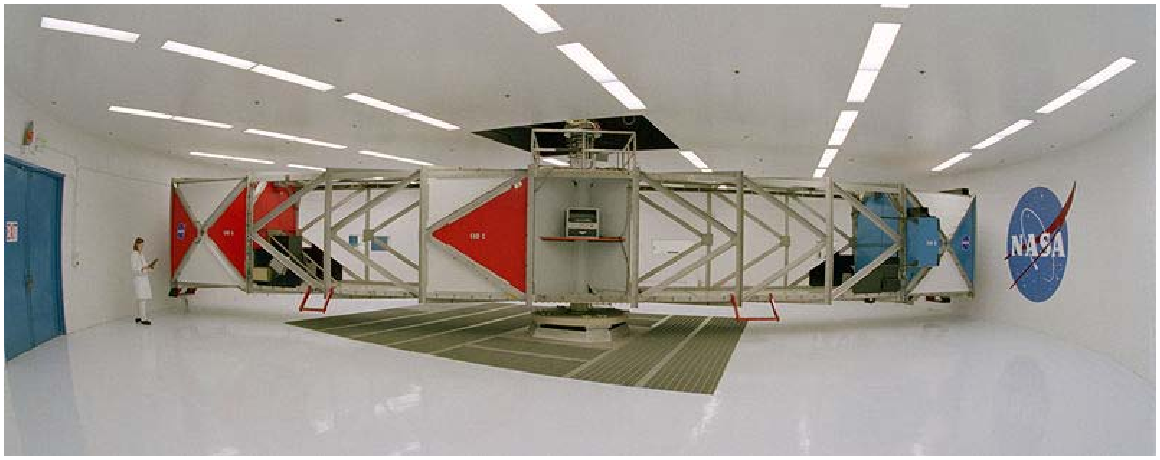
Simple centrifuges are used in chemistry, biology, and biochemistry for isolating and separating suspensions. They vary widely in speed and capacity. They usually comprise a rotor containing two, four, six, or many more numbered wells within which the samples containing centrifuge tips may be placed.

Isotope separation

Other centrifuges, the first being the Zippe-type centrifuge, separate isotopes, and these kinds of centrifuges are in use in nuclear power and nuclear weapon programs.

Gas centrifuges are used in uranium enrichment. The heavier isotope of uranium (uranium-238) in the uranium hexafluoride gas tends to concentrate at the walls of the centrifuge as it spins, while the desired uranium-235 isotope is extracted and concentrated with a scoop selectively placed inside the centrifuge. It takes many thousands of centrifuges to enrich uranium enough for use in a nuclear reactor (around

3.5% enrichment), and many thousands more to enrich it to weapons-grade (above 90% enrichment) for use in nuclear weapons.



The 20 G centrifuge at the NASA Ames Research Center

Aeronautics and astronautics

Human centrifuges are exceptionally large centrifuges that test the reactions and tolerance of pilots and astronauts to acceleration above those experienced in the Earth's gravity.

The US Air Force at Holloman Air Force Base, New Mexico operates a human centrifuge. The centrifuge at Holloman AFB is operated by the aerospace physiology department for the purpose of training and evaluating prospective fighter pilots for high-*g* flight in Air Force fighter aircraft.

The use of large centrifuges to simulate a feeling of gravity has been proposed for future long-duration space missions. Exposure to this simulated gravity would prevent or reduce the bone decalcification and muscle atrophy that affect individuals exposed to long periods of freefall. An example of this can be seen in the film *2001: A Space Odyssey*.

Earthquake and blast simulation

The **geotechnical centrifuge** is used for simulating blasts and earthquake phenomena.

Commercial applications

- Centrifuges with a batch weight of up to 2,200 kg per charge are used in the sugar industry to separate the sugar crystals from the mother liquor.
- Standalone centrifuges for drying (hand-washed) clothes – usually with a water outlet.

- Centrifuges are used in the attraction Mission: SPACE, located at Epcot in Walt Disney World, which propels riders using a combination of a centrifuge and a motion simulator to simulate the feeling of going into space.
- In soil mechanics, centrifuges utilize centrifugal acceleration to match soil stresses in a scale model to those found in reality.
- Large industrial centrifuges are commonly used in water and wastewater treatment to dry sludges. The resulting dry product is often termed **cake**, and the water leaving a centrifuge after most of the solids have been removed is called **centrate**.
- Large industrial centrifuges are also used in the oil industry to remove solids from the drilling fluid.
- Disc-stack centrifuges used by some companies in Oil Sands industry to separate small amounts of water and solids from bitumen
- Centrifuges are used to separate cream (remove fat) from milk.