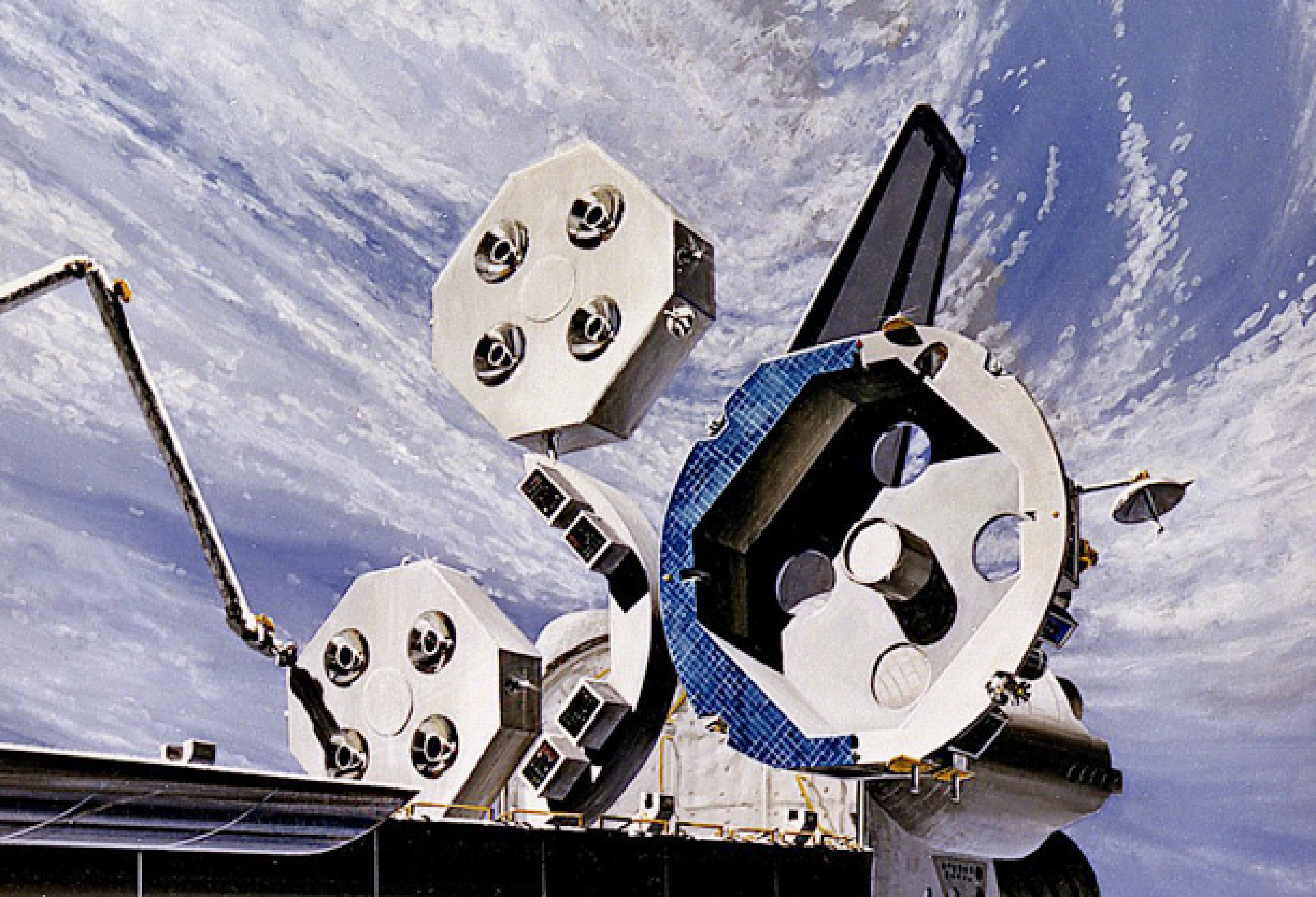

Magnetic Propulsion Devices and Technologies

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Chapter 1

Electromagnetic Propulsion

Electromagnetic propulsion (EMP), is the principle of accelerating an object by the utilization of a flowing electrical current and magnetic fields. The electrical current is used to either create an opposing magnetic field, or to charge a fluid, which can then be repelled. It is well known that when a current flows through a conductor in a magnetic field, an electromagnetic force known as a Lorentz force, pushes the conductor in a direction perpendicular to the conductor and the magnetic field. This repulsing force is what causes propulsion in a system designed to take advantage of the phenomenon. The term electromagnetic propulsion (EMP) can be described by its individual components: electromagnetic- using electricity to create a magnetic field (electromagnetism), and propulsion- the process of propelling something. One key difference between EMP and propulsion achieved by electric motors is that the electrical energy used for EMP is not used to produce rotational energy for motion; though both use magnetic fields and a flowing electrical current.

The science of electromagnetic propulsion does not have origins with any one individual and has applications in many different fields. The thought of using magnets for propulsion continues to this day and has been dreamed of since at least 1897 when John Munro published his fictional story "A Trip to Venus". Current applications can be seen in maglev trains and military railguns. Other applications that remain not widely used or still in development include micro-thrusters for low orbiting satellites and seawater thrusters for ships and submarines.

History

One of the first recorded discoveries regarding electromagnetic propulsion was in 1889 when Professor Elihu Thomson made public his work with electromagnetic waves and alternating currents. A few years later Emile Bachelet proposed the idea of a metal carriage levitated in air above the rails in a modern railway, which he showcased in the early 1890s. In the 1960s Eric Roberts Laithwaite developed the linear induction motor, which built upon these principles and introduced the first practical application of electromagnetic propulsion. In 1966 James R. Powell and Gordon Danby patented the superconducting maglev transportation system, and after this engineers around the world raced to create the first high speed rail. From 1984-1995 the first commercial automated maglev system ran in Birmingham. It was a low speed Maglev shuttle that ran from the Birmingham International Airport to the Birmingham International Railway System.

Uses

Trains

JR-Maglev at Yamanashi, Japan test track in November, 2005. 581 km/h. Guinness World Records authorization.

Electromagnetic propulsion is utilized in transportation systems to minimize friction and maximize speed over long distances. This has mainly been implemented in high-speed rail systems that use a linear induction motor to power trains by magnetic currents. It has also been utilized in theme parks to create high-speed roller coasters and water rides.

Maglev:

In a maglev train the primary coil assembly lies below the reaction plate. There is a 1–10 cm (0.39-3.93 inch) air gap between that eliminates friction, allowing for speeds up to

500 km/h (310 mph). An alternating electric current is supplied to the coils, which creates a change in polarity of the magnetic field. This pulls the train forward from the front, and thrusts the train forward from the back. A typical Maglev train costs three cents per passenger mile, or seven cents per ton mile (not including construction costs). This compares to 15 cents per passenger miles for travel by plane and 30 cents for ton mile for travel by intercity trucks. Maglev tracks have high longevity due to minimal friction and an even distribution of weight. Most last for at least 50 years and require little maintenance during this time. Maglev trains are promoted for their energy efficiency since they run on electricity, which can be produced by coal, nuclear, hydro, fusion, wind or solar power without requiring oil. On average most trains travel 483 km/h (300 mph) and use 0.4 megajoules per passenger mile. Using a 20 mi/gallon car with 1.8 people as a comparison, travel by car is typically 97 khp (60 mph) and uses 4 megajoules per passenger mile. Along with this there are no carbon dioxide emissions and the running of the train is significantly quieter than other trains, trucks or airplanes.

Assembly: Linear Induction Motor

A linear induction motor consists of two parts: the primary coil assembly and the reaction plate. The primary coil assembly consists of phase windings surrounded by steel laminations, and includes a thermal sensor within a thermal epoxy. The reaction plate consists of a 3.2 mm (0.125 inch) thick aluminum or copper plate bonded to a 6.4 mm (0.25 inch) thick cold rolled steel sheet. There is an air gap between these two parts that creates the frictionless property an electromagnetic propulsion system encompasses. Functioning of a linear induction motor begins with an AC force that is supplied to the coil windings within the primary coil assembly. This creates a traveling magnetic field that induces a current in the reaction plate, which then creates its own magnetic field. The magnetic fields in the primary coil assembly and reaction plate alternate, which generates force and direct linear motion.

Aerospace

There are multiple applications for EMP technologies in the field of aerospace. Many of these applications are conceptual as of now, however, there are also several applications that range from near term to next century. One of such applications is the use of EMP to control fine adjustments of orbiting satellites. One of these particular systems is based on the direct interactions of the vehicle's own electromagnetic field and the magnetic field of the earth. The thrust force may be thought of as an electrodynamic force of interaction of the electric current inside its conductors with the applied natural field of the earth. To attain a greater force of interaction, the magnetic field must be propogated further from the flight craft. The advantages of such systems is the very precise and instantaneous control over the thrust force. In addition, the expected electrical efficiencies are far greater than those of current chemical rockets that attain propulsion through the intermediate use of heat; this results in low efficiencies and large amounts of gaseous pollutants. The electrical energy in the coil of the EMP system is translated to potential and kinetic energy through direct energy conversion. This results in the system having the same high efficiencies as other electrical machines while excluding the ejection of any substance into the environment.

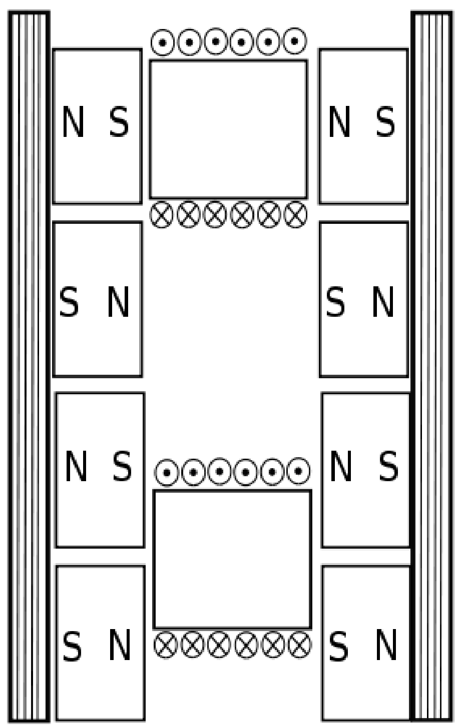
The current thrust-to mass ratios of these systems are relatively low. Nevertheless, since they do not require propulsive mass, the vehicle mass is constant. Also, the thrust can be continuous with relatively low electric consumption. The biggest limitation would be mainly the electrical conductance of materials to produce the necessary values of the current in the propulsion system.

Ships and Submarines

EMP and its applications for seagoing ships and submarines have been investigated since at least 1958 when Warren Rice filled a patent explaining the technology US 2997013. The technology described by Rice considered charging the hull of the vessel itself. The design was later refined by allowing the water to flow through thrusters as described in a later patent by James Meng US 5333444. The arrangement consists of a water channel open at both ends extending longitudinally through or attached to the ship, a means for producing magnetic field throughout the water channel, electrodes at each side of the channel and source of power to send direct current through the channel at right angles to magnetic flux in accordance with Lorentz force.

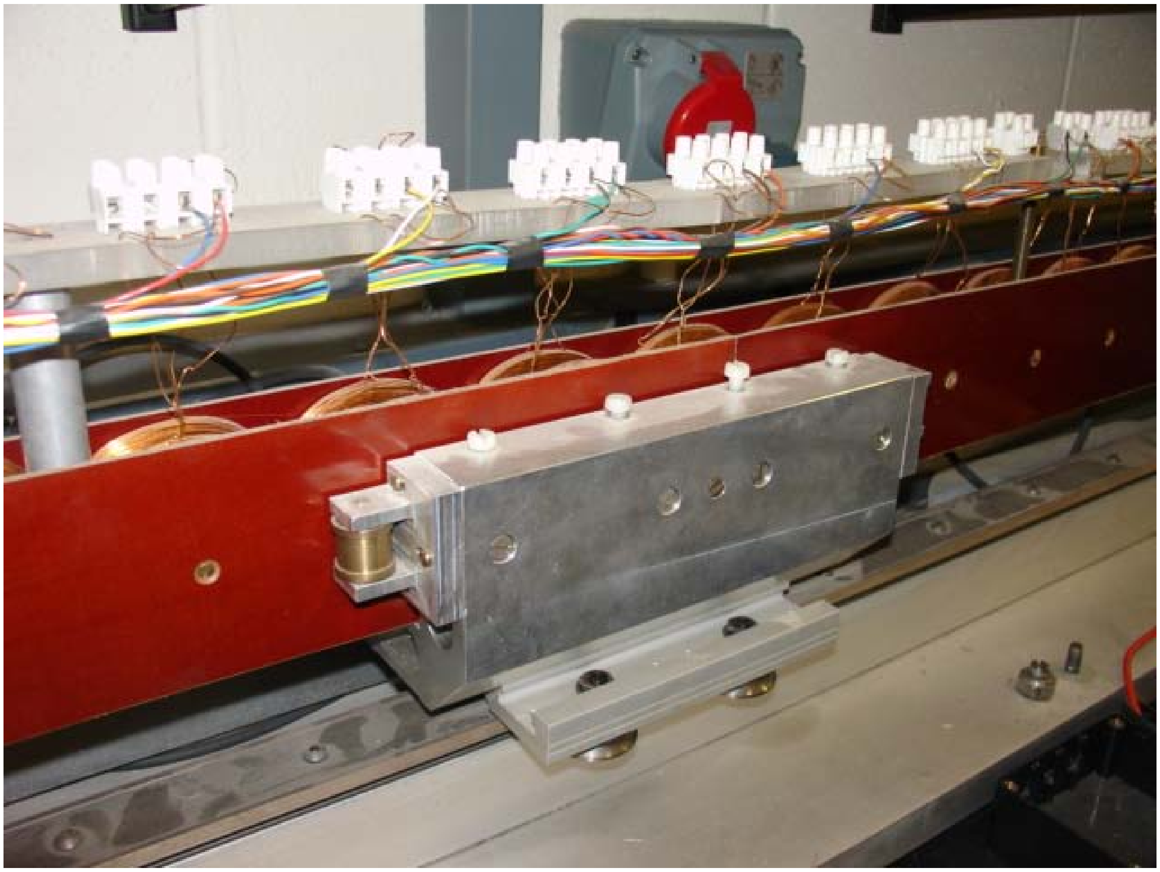
Chapter 2

Linear Motor



Free-body diagram of a U-channel linear motor. The view is perpendicular to the channel axis. The two coils at centre are mechanically connected, and are energized in "quadrature" (with a phase difference of 90° (π/2 radians)). If the bottom coil (as shown) leads in phase, then the motor will move downward (in the drawing), and vice versa.

A linear motor for trains running Toei Oedo line



A prototype of linear motor with visible separate coils

A **linear motor** is an electric motor that has had its stator and rotor "unrolled" so that instead of producing a torque (rotation) it produces a linear force along its length. The most common mode of operation is as a Lorentz-type actuator, in which the applied force is linearly proportional to the current and the magnetic field ($\mathbf{F} = q\mathbf{v} \times \mathbf{B}$).

Many designs have been put forward for linear motors, falling into two major categories, low-acceleration and high-acceleration linear motors. Low-acceleration linear motors are suitable for maglev trains and other ground-based transportation applications. High-acceleration linear motors are normally quite short, and are designed to accelerate an object up to a very high speed and then release it, like roller coasters. They are usually used for studies of hypervelocity collisions, as weapons, or as mass drivers for spacecraft propulsion. The high-acceleration motors are usually of the AC **linear induction motor** (LIM) design with an active three-phase winding on one side of the air-gap and a passive conductor plate on the other side. However, the direct current homopolar linear motor the railgun is another high acceleration linear motor design. The low-acceleration, high speed and high power motors are usually of the **linear synchronous motor** (LSM) design, with an active winding on one side of the air-gap and an array of alternate-pole magnets on the other side. These magnets can be permanent magnets or energized magnets. The Transrapid Shanghai motor is an LSM.

Low acceleration

The history of linear electric motors can be traced back at least as far as the 1840s, to the work of Charles Wheatstone at King's College in London, but Wheatstone's model was too inefficient to be practical. A feasible linear induction motor is described in the US patent 782312 (1905 - inventor Alfred Zehden of Frankfurt-am-Main), for driving trains or lifts. The German engineer Hermann Kemper built a working model in 1935. In the late 1940s, professor Eric Laithwaite of Imperial College in London developed the first full-size working model. In his design, and in most low-acceleration designs, the force is produced by a moving linear magnetic field acting on conductors in the field. Any conductor, be it a loop, a coil or simply a piece of plate metal, that is placed in this field will have eddy currents induced in it thus creating an opposing magnetic field, in accordance with Lenz's law. The two opposing fields will repel each other, thus forcing the conductor away from the stator and carrying it along in the direction of the moving magnetic field. He called the later versions of it magnetic river.

Because of these properties, linear motors are often used in maglev propulsion, as in the Japanese Linimo magnetic levitation train line near Nagoya. However, linear motors have been used independently of magnetic levitation, as in Bombardier's Advanced Rapid Transit systems worldwide and a number of modern Japanese subways, including Tokyo's Toei Oedo Line.

Similar technology is also used in some roller coasters with modifications but, at present, is still impractical on street running trams, although this, in theory, could be done by burying it in a slotted conduit.

ART trains propel themselves using an aluminium induction strip placed between the rails.

Outside of public transportation, vertical linear motors have been proposed as lifting mechanisms in deep mines, and the use of linear motors is growing in motion control applications. They are also often used on sliding doors, such as those of low floor trams such as the Citadis and the Eurotram. Dual axis linear motors also exist. These specialized devices have been used to provide direct *X*-*Y* motion for precision laser cutting of cloth and sheet metal, automated drafting, and cable forming. Mostly used linear motors are LIM (linear induction motor), LSM (linear synchronous motor). Linear DC motors are not used as it includes more cost and linear SRM suffers from poor thrust. So for long run in traction LIM is mostly preferred and for short run LSM is mostly preferred.

From concept to industrial use

In the 1980s, British engineer Hugh-Peter Kelly designed the first tubular linear motor by enclosing the permanent magnets in a sealed stainless steel cylinder. It was brought to market by linear motor manufacturer Linear Drives (now Copley Motion Systems). The patented permanent magnet arrangement induces a sinusoidal response in the coils that are enclosed in a square profile body. This allowed machine builders to use the new linear motors with standard sinusoidal servo drives commonly used in motion control.

Tubular linear motors

Tubular linear motors are more rugged than early flat-bed and U-channel linear motors allowing them to be used in dirty industrial environments such as food packaging and machine tools. The tubular construction protects the permanent magnets from the external environment and automatically balances attractive forces so that the motor is easier to integrate into machines. These motors operate at 5–9 m/s (15–30 ft/s) with high acceleration for dynamic motion control.

A new type of linear motor, called the ServoTube has allowed linear motors to be used in industrial environments by integrating the position sensing electronics into the motor body (called a forcer).

High acceleration

High-acceleration linear motors have been suggested for a number of uses. They have been considered for use as weapons, since current armour-piercing ammunition tends to consist of small rounds with very high kinetic energy, for which just such motors are suitable. Many amusement park roller coasters now use linear induction motors to propel the train at a high speed, as an alternative to using a lift hill. The United States Navy is also using linear induction motors in the Electromagnetic Aircraft Launch System that will replace traditional steam catapults on future aircraft carriers. They have also been suggested for use in spacecraft propulsion. In this context they are usually called mass drivers. The simplest way to use mass drivers for spacecraft propulsion would be to build a large mass driver that can accelerate cargo up to escape velocity.

High-acceleration linear motors are difficult to design for a number of reasons. They require large amounts of energy in very short periods of time. One rocket launcher design calls for 300 GJ for each launch in the space of less than a second. Normal electrical generators are not designed for this kind of load, but short-term electrical energy storage methods can be used. Capacitors are bulky and expensive but can supply large amounts of energy quickly. Homopolar generators can be used to convert the kinetic energy of a flywheel into electric energy very rapidly. High-acceleration linear motors also require very strong magnetic fields; in fact, the magnetic fields are often too strong to permit the use of superconductors. However, with careful design, this need not be a major problem.

Two different basic designs have been invented for high-acceleration linear motors: railguns and coilguns.

Usages of a linear motor for train propulsion

Usage with conventional rails

All applications are in rapid transit.

Guangzhou Metro L4 vehicle made by CSR Sifang Locomotive and Rolling Stock & Kawasaki Heavy Industries

Guangzhou Metro L5 vehicle made by CSR Sifang Locomotive and Rolling Stock and Kawasaki Heavy Industries

- Bombardier ART:
    - Airport Express in Beijing (opened 2008)
    - AirTrain JFK in New York (opened 2003)
    - Detroit People Mover in Detroit (opened 1987)
    - EverLine Rapid Transit System in Yongin (under construction)
    - Kelana Jaya Line in Kuala Lumpur (opened 1998)
    - Scarborough RT in Toronto (using UTDC's (predecessor) ICTS technology - opened 1985)
    - SkyTrain in Vancouver (Expo Line (using ITCS) opened 1985 and Millennium Line opened in 2002)
    - Beijing Subway Capital Airport Track (opened 2008)

- Several subways in Japan and China, built by Kawasaki Heavy Industries:
    - Limtrain in Saitama (short-lived demonstration track, 1988)
    - Nagahori Tsurumi-ryokuchi Line in Osaka (opened 1990)
    - Toei Ōedo Line in Tokyo (opened 2000)
    - Kaigan Line in Kobe (opened 2001)
    - Nanakuma Line in Fukuoka (opened 2005)
    - Imazatosuji Line in Osaka (opened 2006)

- Green Line in Yokohama (opened 2008)
- Tōzai Line in Sendai (under construction)
- Line 4 of Guangzhou Metro in Guangzhou, China (opened 2005).
- Line 5 of Guangzhou Metro in Guangzhou, China (open in December 2009).
- Line 6 of Guangzhou Metro in Guangzhou, China (under construction).

Both the Kawasaki trains and Bombardier's ART have the active part of the motor in the cars and use overhead wires (Japanese Subways) or a third rail (ART) to transfer power to the train.

Usage with monorails

- There is at least one known monorail system which is **not** magnetically levitated, but nonetheless uses linear motors. This is the Moscow Monorail. Originally, traditional motors and wheels were to be used. However, it was discovered during test runs that the proposed motors and wheels would fail to provide adequate traction under some conditions, for example, when ice appeared on the rail. Hence, wheels are still used, but the trains use linear motors to accelerate and slow down. This is possibly the only use of such a combination, due to the lack of such requirements for other train systems.

- The TELMAGV is a prototype of a monorail system that is also not magnetically levitated but uses linear motors.

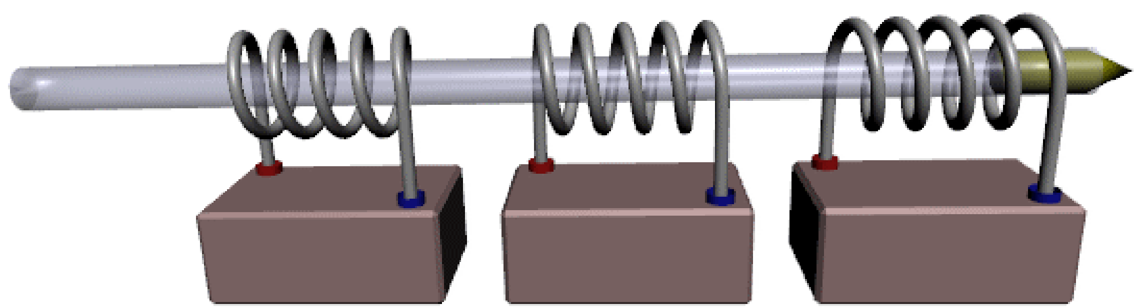
Usage with magnetic levitation

- High-speed trains:
  - Transrapid: first commercial use in Shanghai (opened in 2004)
  - JR-Maglev

- Rapid transit:
  - Birmingham Airport, UK (opened 1984, closed 1995)
  - M-Bahn in Berlin, Germany (opened in 1989, closed in 1991)
  - Daejeon EXPO, Korea (ran only 1993)
  - HSST: Linimo line in Aichi, Japan (opened 2005)

Chapter 3

Coilgun



Simplified diagram of a multistage coilgun with three coils, a barrel, and a ferromagnetic projectile

A **coilgun** is a type of projectile accelerator that consists of one or more coils used as electromagnets in the configuration of a synchronous linear motor which accelerate a magnetic projectile to high velocity. The name **Gauss gun** is sometimes used for such devices in reference to Carl Friedrich Gauss, who formulated mathematical descriptions of the magnetic effect used by magnetic accelerators.

Coilguns consist of one or more coils arranged along the barrel that are switched in sequence so as to ensure that the projectile is accelerated quickly along the barrel via magnetic forces. Coilguns are distinct from railguns, which pass a large current through the projectile or sabot via sliding contacts. Coilguns and railguns also operate on different principles. The first operational coilgun was developed and patented by Norwegian physicist Kristian Birkeland.

In 1934 an American inventor developed a machine gun based similar in concept to the coilgun. Except for a photo in a few publications, very little is known about it.

Construction

A coilgun, as the name implies, consists of a coil of wire, an electromagnet, with a ferromagnetic projectile placed at one of its ends. Effectively a coilgun is a solenoid, a current-carrying coil which will draw a ferromagnetic object through its center. A large current is pulsed through the coil of wire and a strong magnetic field forms, pulling the projectile to the center of the coil. When the projectile nears this point the electromagnet is switched off and the next electromagnet can be switched on, progressively accelerating the projectile down successive stages. In common coilgun designs the "barrel" of the gun is made up of a track that the projectile rides on, with the driver into the magnetic coils around the track. Power is supplied to the electromagnet from some sort of fast discharge storage device, typically a battery or high-capacity high voltage capacitors designed for fast energy discharge. A diode is used to protect polarity sensitive capacitors (such as electrolytics) from damage due to inverse polarity of the current after the discharge.

There are two main types or setups of a coilgun: single-stage and multistage. A single-stage coilgun uses one electromagnet to propel a ferromagnetic projectile. A multistage coilgun uses several electromagnets in succession to progressively increase the speed of the projectile.

Many hobbyists use low-cost rudimentary designs to experiment with coilguns, for example using photoflash capacitors from a disposable camera, or a capacitor from a standard cathode-ray tube television as the energy source, and a low inductance coil to propel the projectile forward.

A superconducting coilgun called a *quench gun* could be created by successively quenching a line of adjacent coaxial superconducting coils forming a gun barrel, generating a wave of magnetic field gradient traveling at any desired speed. A traveling superconducting coil might be made to ride this wave like a surfboard. The device would be a mass driver or linear synchronous motor with the propulsion energy stored directly in the drive coils.

Switching

One main obstacle in coilgun design is switching the power through the coils. There are several common solutions — the simplest (and probably least effective) is the spark gap, which releases the stored energy through the coil when the voltage reaches a certain threshold. A better option is to use solid-state switches; these include IGBTs or power MOSFETs (which can be switched off mid-pulse) and SCRs (which release all stored energy before turning off). A quick-and-dirty method for switching, especially for those using a flash camera for the main components, is to use the flash tube itself as a switch. By wiring it in series with the coil, it can silently and non-destructively (assuming that the energy in the capacitor is kept below the tube's safe operating limits) allow a large amount of current to pass through to the coil. Like any flash tube, ionizing the gas in the tube with a high voltage triggers it. However, a large amount of the energy will be dissipated as heat and light, and, due to the tube being a spark gap, the tube will stop conducting once the voltage across it drops sufficiently, leaving some charge remaining on the capacitor.

A multistage coilgun

Resistance

The electrical resistance of the coils and the equivalent series resistance (ESR) of the current source limit the efficiency of a coilgun.

The magnetic circuit

Ideally, 100% of the magnetic flux generated by the coil would be delivered to and act on the projectile, but this is often far from the case due to the common air-core-solenoid / projectile construction of most coilguns.

Since an air-cored solenoid is simply an inductor, the majority of the magnetic flux is not coupled into the projectile, instead being stored in the surrounding air. The energy that is stored in this field does not simply disappear from the magnetic circuit once the capacitor finishes discharging; much of it returns to the capacitor when the circuit's electric current is decreasing. As the coilgun circuit is inherently analogous to an LC oscillator, it does this in the reverse direction ('ringing'), which can seriously damage polarized capacitors such as electrolytic capacitors, which are far cheaper and smaller for a given capacity than other types.

The capacitor charging to a negative voltage can be prevented by placing a diode across the capacitor terminals; this diode and the coil must dissipate all of the stored energy as heat. While this is a simple and effective solution, it requires expensive high-power semiconductors, and a coil which will not overheat.

Some designs attempt to recover the energy stored in the magnetic field by using a pair of diodes. These diodes, instead of being forced to dissipate the remaining energy, recharge the capacitors with the right polarity to be used again for the next discharge cycle. This will also avoid the need to recharge the capacitors from zero, thus significantly reducing charge times.

In order to reduce component size, weight, durability requirements, and most importantly, cost, the magnetic circuit must be optimized to deliver more energy to the projectile per discharge cycle while still using the same energy input. This has been addressed to some extent by the use of end iron and back iron, which are pieces of magnetic material that enclose the coil and help reduce the reluctance of the magnetic circuit. The results of this vary widely, due to the use of materials ranging anywhere from magnetic steel to video tape. The inclusion of an additional piece of magnetic material in the magnetic circuit also magnifies the problems of flux saturation and other magnetic losses.

Projectile saturation

Another significant limitation of the coilgun is the occurrence of ferromagnetic projectile saturation. When the flux in the projectile lies in the linear portion of its material's B(H) curve, the force applied to the core is proportional to the square of coil current (I) - the field (H) is linearly dependent on I, B is linearly dependent on H and force is linearly dependent on the product BI. This relationship continues until the core is saturated; once this happens B will only increase marginally with H (and thus with I), so force gain is linear. Since losses are proportional to I^2, increasing current beyond this point eventually decreases efficiency although it may increase the force. This puts an absolute limit on how much a given projectile can be accelerated with a single stage at acceptable efficiency.

Projectile magnetization and reaction time

Apart from saturation, the B(H) dependency often contains a hysteresis loop and the reaction time of the projectile material may be significant. The hysteresis means that the projectile becomes permanently magnetized and some energy will be lost as a permanent magnetic field of the projectile. The projectile reaction time, on the other hand, makes the projectile reluctant to respond to abrupt B changes; the flux will not rise as fast as desired while current is applied and a B tail will occur after the coil field has disappeared. This delay decreases the force, which would be maximized if the H and B were in phase.

Chapter 4

Electrodynamic Tether

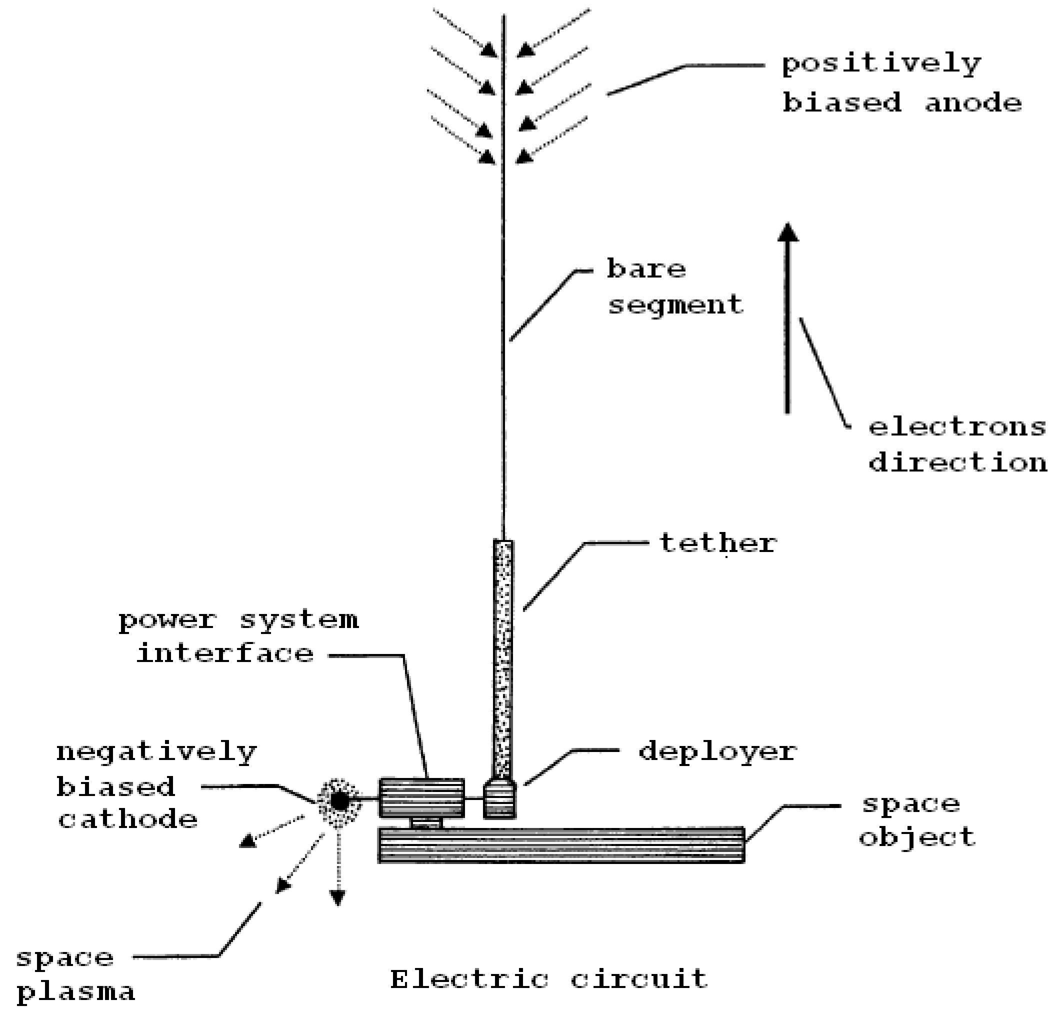
Medium close-up view, captured with a 70mm camera, shows Tethered Satellite System deployment.

Electrodynamic tethers are long conducting wires, such as one deployed from a tether satellite, which can operate on electromagnetic principles as generators, by converting their kinetic energy to electrical energy, or as motors, converting electrical energy to kinetic energy. Electric potential is generated across a conductive tether by its motion through the Earth's magnetic field. The choice of the metal conductor to be used in an electrodynamic tether is determined by a variety of factors. Primary factors usually include high electrical conductivity, and low density. Secondary factors, depending on the application, include cost, strength, and melting point.

Tether propulsion

As part of a *tether propulsion* system, crafts can use long, strong conductors (though not all tethers are conductive) to change the orbits of spacecraft. It has the potential to make space travel significantly cheaper. It is a simplified, very low-budget magnetic sail. It can be used either to accelerate or brake an orbiting spacecraft. When direct current is pumped through the tether, it exerts a force against the magnetic field, and the tether accelerates the spacecraft.

Tethers as generators



A space object, i.e. a satellite in Earth orbit, or any other space object either natural or man made, is physically connected to the tether system. The tether system comprises a deployer from which a conductive tether having a bare segment extends upward from space object. The positively biased anode end of tether collects electrons from the ionosphere as space object moves in direction across the Earth's magnetic field. These electrons flow through the conductive structure of the tether to the power system interface, where it supplies power to an associated load, not shown. The electrons then flow to the negatively biased cathode where electrons are ejected into the space plasma, thus completing the electric circuit. (source: U.S. Patent 6,116,544, "Electrodynamic Tether And Method of Use".)

An electrodynamic tether is attached to an object, the tether being oriented at an angle to the local vertical between the object and a planet with a magnetic field. When the tether cuts the planet's magnetic field, it generates a current, and thereby converts some of the orbiting body's kinetic energy to electrical energy. As a result of this process, an electrodynamic force acts on the tether and attached object, slowing their orbital motion. The tether's far end can be left bare, making electrical contact with the ionosphere. Functionally, electrons flow from the space plasma into the conductive tether, are passed through a resistive load in a control unit and are emitted into the space plasma by an electron emitter as free electrons. In principle, compact high-current tether power generators are possible and, with basic hardware, 10 to 25 kilowatts appears to be attainable.

Voltage and current

NASA has conducted several experiments with Plasma Motor Generator (PMG) tethers in space. An early experiment used a 500 meter conducting tether. In 1996, NASA conducted an experiment with a 20,000-meter conducting tether. When the tether was fully deployed during this test, the orbiting tether generated a potential of 3,500 volts. This conducting single-line tether was severed after five hours of deployment. It is believed that the failure was caused by an electric arc generated by the conductive tether's movement through the Earth's magnetic field.

When a tether is moved at a velocity (*v*) at right angles to the Earth's magnetic field (**B**), an electric field is observed in the tether's frame of reference. This can be stated as:

$$\mathbf{E} = v * \mathbf{B} = v\mathbf{B}$$

The direction of the electric field (**E**) is at right angles to both the tether's velocity (*v*) and magnetic field (**B**). If the tether is a conductor, then the electric field leads to the displacement of charges along the tether. Note that the velocity used in this equation is the orbital velocity of the tether. The rate of rotation of the Earth, or of its core, is not relevant.

Voltage across conductor

With a long conducting wire of length ***L***, an electric field ***E*** is generated in the wire. It produces a voltage *V* between the opposite ends of the wire. This can be expressed as:

$$V = \mathbf{E} \cdot \mathbf{L} = EL\cos\tau = vBL\cos\tau$$

where the angle τ is between the length vector (***L***) of the tether and the electric field vector (***E***), assumed to be in the vertical direction at right angles to the velocity vector (***v***) in plane and the magnetic field vector (***B***) is out of the plane.

Current in conductor

An electrodynamic tether can be described as a type of thermodynamically "open system". Electrodynamic tether circuits cannot be completed by simply using another wire, since another tether will develop a similar voltage. Fortunately, the Earth's magnetosphere is not "empty", and, in near-Earth regions (especially near the Earth's atmosphere) there exist highly electrically conductive plasmas which are kept partially ionized by solar radiation or other radiant energy. The electron and ion density varies according to various factors, such as the location, altitude, season, sunspot cycle, and contamination levels. It is known that a positively charged bare conductor can readily remove free electrons out of the plasma. Thus, to complete the electrical circuit, a sufficiently large area of uninsulated conductor is needed at the upper, positively charged end of the tether, thereby permitting current to flow through the tether.

However, it is more difficult for the opposite (negative) end of the tether to eject free electrons or to collect positive ions from the plasma. It is plausible that, by using a very large collection area at one end of the tether, enough ions can be collected to permit significant current through the plasma. This was demonstrated during the Shuttle orbiter's TSS-1R mission, when the shuttle itself was used as a large plasma contactor to provide over an ampere of current. Improved methods include creating an electron emitter, such as a thermionic cathode, plasma cathode, plasma contactor, or field electron emission device. Since both ends of the tether are "open" to the surrounding plasma, electrons can flow out of one end of the tether while a corresponding flow of electrons enters the other end. In this fashion, the voltage that is electromagnetically induced within the tether can cause current to flow through the surrounding space environment, completing an electrical circuit through what appears to be, at first glance, an open circuit.

Tether current

The amount of current (I) flowing through a tether depends on various factors. One of these is the circuit's total resistance (R). The circuit's resistance consist of three components:

1. the effective resistance of the plasma,
2. the resistance of the tether, and
3. a control variable resistor.

In addition, a parasitic load is needed. The load on the current may take the form of a charging device which, in turn, charges reserve power sources such as batteries. The batteries in return will be used to control power and communication circuits, as well as drive the electron emitting devices at the negative end of the tether. As such the tether can be completely self-powered, besides the initial charge in the batteries to provide electrical power for the deployment and startup procedure.

The charging battery load can be viewed as a resistor which absorbs power, but stores this for later use (instead of immediately dissipating heat). It is included as part of the "control resistor". The charging battery load is not treated as a "base resistance" though, as the charging circuit can be turned off at anytime. When off, the operations can be continued without interruption using the power stored in the batteries.

Challenges

One complication to these techniques is that if the tether rotates, the direction of current must reverse (such as is the case in alternating currents of alternators). Others include pendular motion instability and electrical surges.

Pendular motion instability

Electrodynamic tethers deployed along the local vertical ('hanging tethers') may suffer from dynamical instability. Pendular motion causes the tether vibration amplitude to build up under the action of electromagnetic interaction. As the mission time increases, this behavior can compromise the performance of the system. Over a few weeks, electrodynamic tethers in Earth orbit might build up vibrations in many modes, as their orbit interacts with irregularities in magnetic and gravitational fields.

One plan to control the vibrations is to actively vary the tether current to counteract the growth of the vibrations. Electrodynamic tethers can be stabilized by reducing their current when it would feed the oscillations, and increasing it when it opposes oscillations. Simulations have demonstrated that this can control tether vibration. This approach requires sensors to measure tether vibrations, which can either be an inertial navigation system on one end of the tether, or satellite navigation systems mounted on the tether, transmitting their positions to a receiver on the end.

Another proposed method is to utilise spinning electrodynamic tethers instead of hanging tethers. The gyroscopic effect provides passive stabilisation, avoiding the instability.

Surges

As mentioned earlier, conductive tethers have failed from unexpected current surges. Unexpected electrostatic discharges have cut tethers, damaged electronics, and welded tether handling machinery. It may be that the Earth's magnetic field is not as homogeneous as some engineers have believed.

Chapter 5

Electric Motor

Electric motors

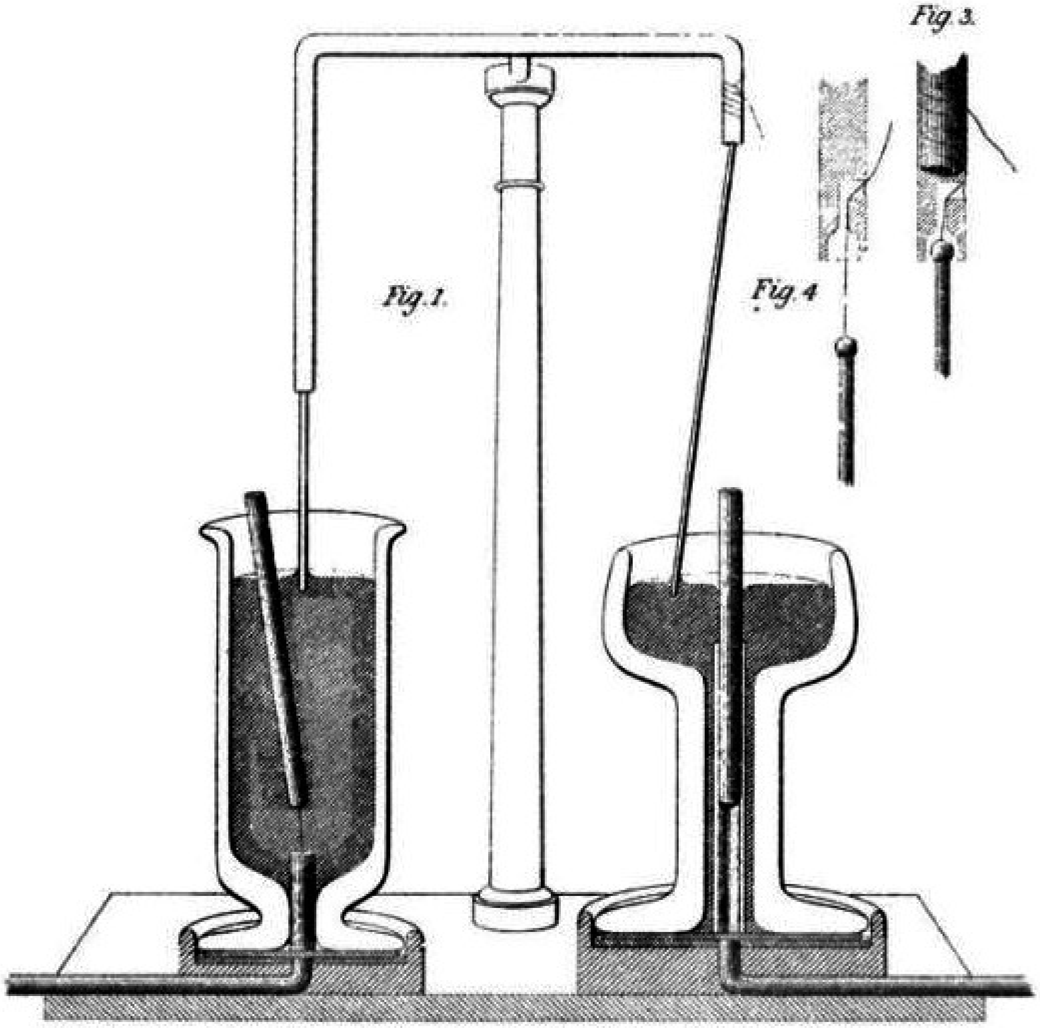
An **electric motor** converts electrical energy into mechanical energy. Most electric motors operate through interacting magnetic fields and current-carrying conductors to generate force, although electrostatic motors use electrostatic forces. The reverse process, producing electrical energy from mechanical energy, is done by generators such as an alternator or a dynamo. Many types of electric motors can be run as generators, and vice versa. For example a starter/generator for a gas turbine, or traction motors used on vehicles, often perform both tasks. Electric motors and generators are commonly referred to as electric machines.

Electric motors are 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 (e.g., 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 ships, pipeline compressors, and water pumps with ratings in the millions of watts. Electric motors may be classified by the source of electric power, by their internal construction, by their application, or by the type of motion they give.

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.

Some devices, such as magnetic solenoids and loudspeakers, although they generate some mechanical power, are not generally referred to as electric motors, and are usually termed actuators and transducers, respectively.

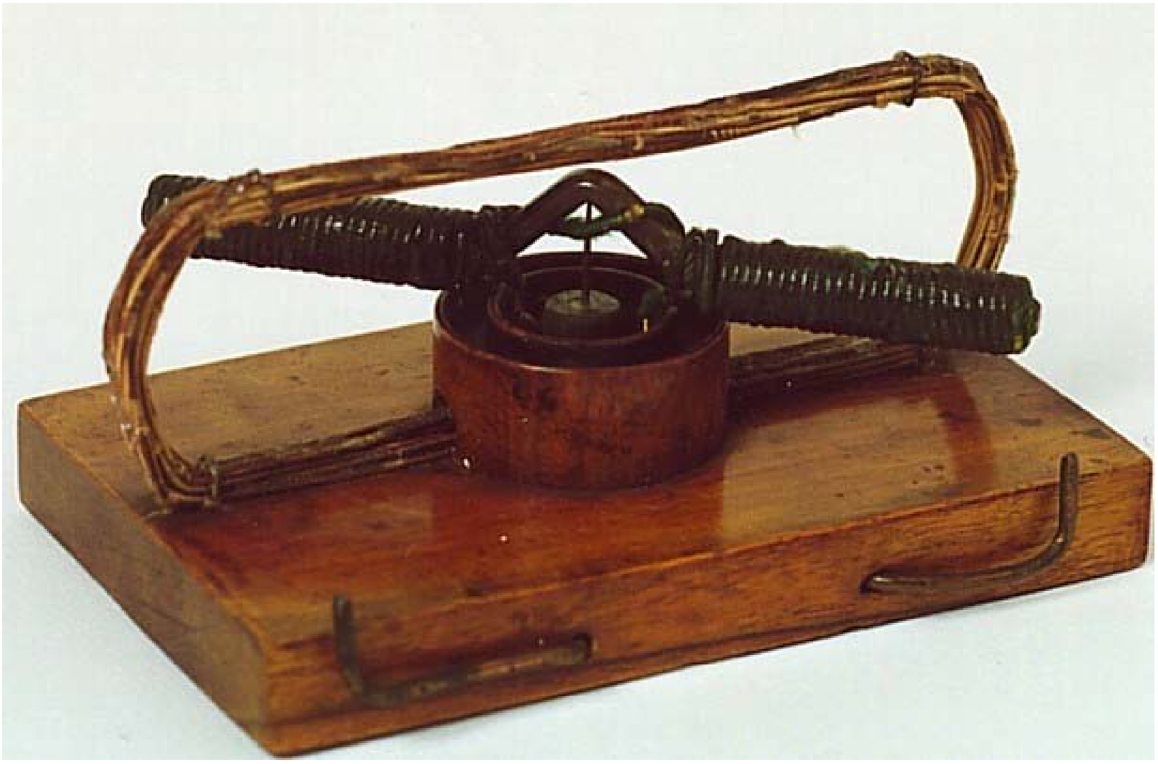
History and development



Faraday's electromagnetic experiment, 1821

Proof of principle

The conversion of electrical energy into mechanical energy by an electromagnetic means was demonstrated by the British scientist Michael Faraday in 1821. A free-hanging wire was dipped into a pool of mercury, on which a permanent magnet was placed. When a current was passed through the wire, the wire rotated around the magnet, showing that the current gave rise to a close circular magnetic field around the wire. This motor is often demonstrated in school physics classes, but brine (salt water) is sometimes used in place of the toxic mercury. This is the simplest form of a class of devices called homopolar motors. A later refinement is the Barlow's wheel. These were demonstration devices only, unsuited to practical applications due to their primitive construction.



Jedlik's "electromagnetic self-rotor", 1827 (Museum of Applied Arts, Budapest. The historic motor still works perfectly today.)

In 1827, Hungarian physicist Ányos Jedlik started experimenting with devices he called "electromagnetic self-rotors". Although they were used only for instructional purposes, in 1828 Jedlik demonstrated the first device to contain the three main components of practical direct current motors: the stator, rotor and commutator. The device employed no permanent magnets, as the magnetic fields of both the stationary and revolving components were produced solely by the currents flowing through their windings.

The first electric motors

The first commutator-type direct current electric motor capable of turning machinery was invented by the British scientist William Sturgeon in 1832. Following Sturgeon's work, a commutator-type direct-current electric motor made with the intention of commercial use was built by Americans Emily and Thomas Davenport and patented in 1837. Their motors ran at up to 600 revolutions per minute, and powered machine tools and a printing press. Due to the high cost of the zinc electrodes required by primary battery power, the motors were commercially unsuccessful and the Davenports went bankrupt. Several inventors followed Sturgeon in the development of DC motors but all encountered the same cost issues with primary battery power. No electricity distribution had been developed at the time. Like Sturgeon's motor, there was no practical commercial market for these motors.

In 1855 Jedlik built a device using similar principles to those used in his electromagnetic self-rotors that was capable of useful work. He built a model electric motor-propelled vehicle that same year. There is no evidence that this experimentation was communicated to the wider scientific world at that time, or that it influenced the development of electric motors in the following decades.

The modern DC motor was invented by accident in 1873, when Zénobe Gramme connected the dynamo he had invented to a second similar unit, driving it as a motor. The Gramme machine was the first electric motor that was successful in the industry.

In 1886 Frank Julian Sprague invented the first practical DC motor, a non-sparking motor capable of constant speed under variable loads. Other Sprague electric inventions about this time greatly improved grid electric distribution (prior work done while employed by Thomas Edison), allowed power from electric motors to be returned to the electric grid, provided for electric distribution to trolleys via overhead wires and the trolley pole, and provided controls systems for electric operations. This allowed Sprague to use electric motors to invent the first electric trolley system in 1887–88 in Richmond VA, the electric elevator and control system in 1892, and the electric subway with independently powered centrally controlled cars, which was first installed in 1892 in Chicago by the South Side Elevated Railway where it became popularly known as the "L". Sprague's motor and related inventions led to an explosion of interest and use in electric motors for industry, while almost simultaneously another great inventor was developing its primary competitor, which would become much more widespread.

In 1888 Nikola Tesla invented the first practicable AC motor and with it the polyphase power transmission system. Tesla continued his work on the AC motor in the years to follow at the Westinghouse company.

The development of electric motors of acceptable efficiency was delayed for several decades by failure to recognize the extreme importance of a relatively small air gap between rotor and stator. Efficient designs have a comparatively small air gap.

The St. Louis motor, long used in classrooms to illustrate motor principles, is extremely inefficient for the same reason, as well as appearing nothing like a modern motor. Photo of a traditional form of the St. Louis motor:

Application of electric motors revolutionized industry. Industrial processes were no longer limited by power transmission using shaft, belts, compressed air or hydraulic pressure. Instead every machine could be equipped with its own electric motor, providing easy control at the point of use, and improving power transmission efficiency. Electric motors applied in agriculture eliminated human and animal muscle power from such tasks as handling grain or pumping water. Household uses of electric motors reduced heavy labor in the home and made higher standards of convenience, comfort and safety possible. Today, electric motors consume more than half of all electric energy produced.

Categorization of electric motors

The classic division of electric motors has been that of Alternating Current (AC) types vs Direct Current (DC) types. This is more a *de facto* convention, rather than a rigid distinction. For example, many classic DC motors run on AC power, these motors being referred to as universal motors.

Rated output power is also used to categorize motors, those of less than 746 Watts, for example, are often referred to as fractional horsepower motors (FHP) in reference to the old imperial measurement.

The ongoing trend toward electronic control further muddles the distinction, as modern drivers have moved the commutator out of the motor shell. For this new breed of motor, driver circuits are relied upon to generate sinusoidal AC drive currents, or some approximation thereof. The two best examples are: the brushless DC motor and the stepping motor, both being poly-phase AC motors requiring external electronic control, although historically, stepping motors (such as for maritime and naval gyrocompass repeaters) were driven from DC switched by contacts.

Considering all rotating (or linear) electric motors require synchronism between a moving magnetic field and a moving current sheet for average torque production, there is a clearer distinction between an asynchronous motor and synchronous types. An asynchronous motor requires slip between the moving magnetic field and a winding set to induce current in the winding set by mutual inductance; the most ubiquitous example being the common AC induction motor which must slip to generate torque. In the synchronous types, induction (or slip) is not a requisite for magnetic field or current production (e.g. permanent magnet motors, synchronous brush-less wound-rotor doubly-fed electric machine).

DC motors

A DC motor is designed to run on DC electric power. Two examples of pure DC designs are Michael Faraday's homopolar motor (which is uncommon), and the ball bearing motor, which is (so far) a novelty. By far the most common DC motor types are the brushed and brushless types, which use internal and external commutation respectively to periodically reverse the current in the rotor windings.

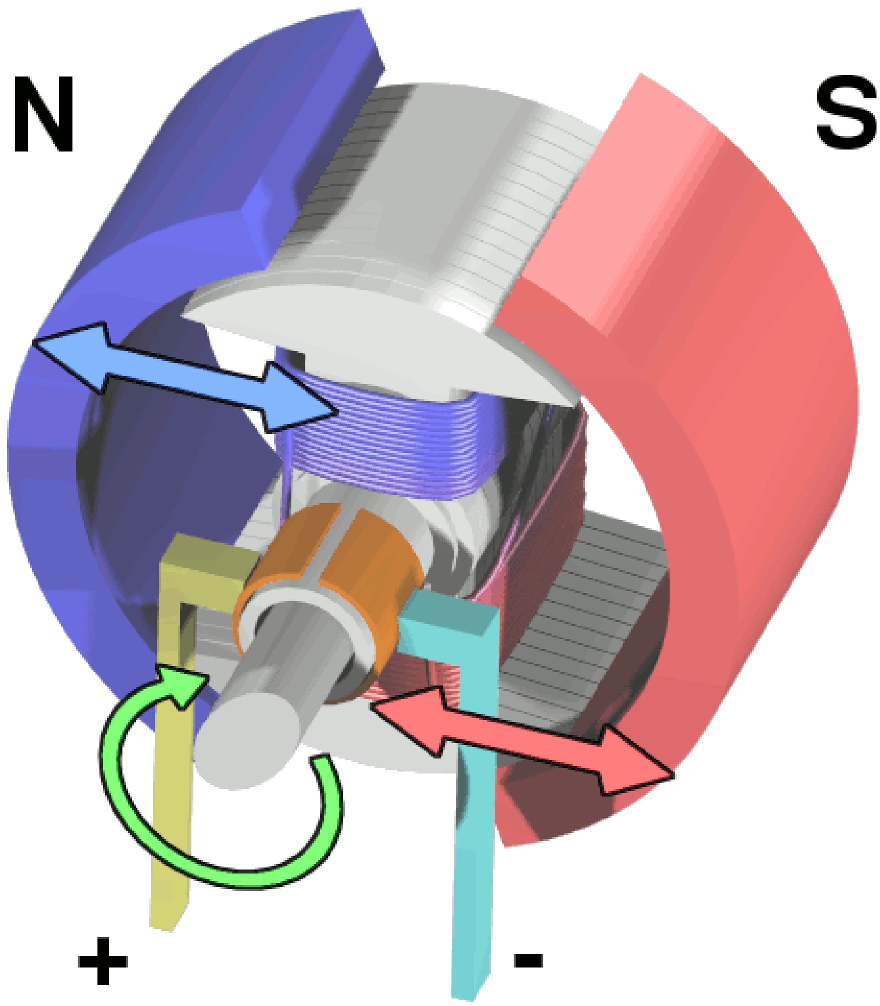
Permanent-magnet motors

A permanent-magnet motor does not have a field winding on the stator frame, instead relying on permanent magnets to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commuation under load. Because this field is fixed, it cannot be adjusted for speed control. Permanent-magnet motors are convenient in miniature motors to eliminate the power consumption of the field winding. Most larger

DC motors are of the "dynamo" type, which requires current to flow in field windings to provide the stator magnetic field.

To minimize overall weight and size, miniature permanent-magnet motors may use high energy magnets made with neodymium or other strategic elements. With the higher flux density provided, electric machines with high energy permanent magnets are at least competitive with all optimally designed singly-fed synchronous and induction electric machines.

Brushed DC motors

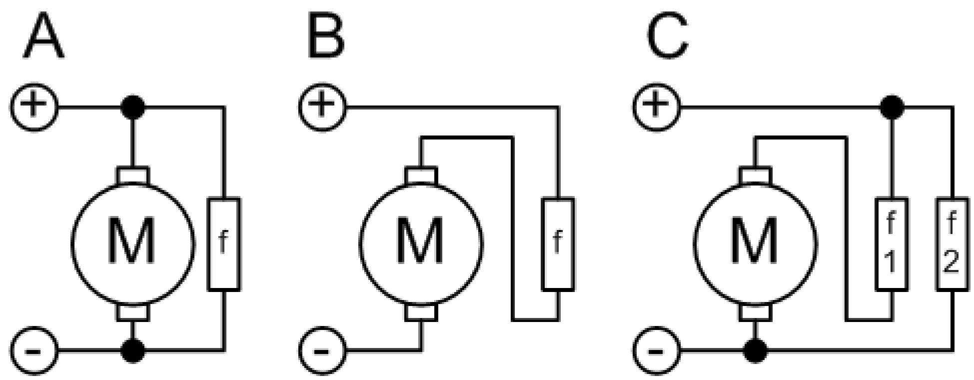


Workings of a brushed electric motor

DC motor design generates an oscillating current in a wound rotor, or armature, with a split ring commutator, and either a wound or permanent magnet stator. A rotor consists of one or more coils of wire wound around a core on a shaft; an electrical power source is connected to the rotor coil through the commutator and its brushes, causing current to flow in it, producing electromagnetism. The commutator causes the current in the coils to be switched as the rotor turns, keeping the magnetic poles of the rotor from ever fully aligning with the magnetic poles of the stator field, so that the rotor never stops (like a compass needle does) but rather keeps rotating indefinitely (as long as power is applied and is sufficient for the motor to overcome the shaft torque load and internal losses due to friction, etc.)

Many of the limitations of the classic commutator DC motor are due to the need for brushes to press against the commutator. This creates friction. Sparks are created by the brushes making and breaking circuits through the rotor coils as the brushes cross the insulating gaps between commutator sections. Depending on the commutator design, this may include the brushes shorting together adjacent sections—and hence coil ends—momentarily while crossing the gaps. Furthermore, the inductance of the rotor coils causes the voltage across each to rise when its circuit is opened, increasing the sparking of the brushes. This sparking limits the maximum speed of the machine, as too-rapid sparking will overheat, erode, or even melt the commutator. The current density per unit area of the brushes, in combination with their resistivity, limits the output of the motor. The making and breaking of electric contact also causes electrical noise, and the sparks additionally cause RFI. Brushes eventually wear out and require replacement, and the commutator itself is subject to wear and maintenance (on larger motors) or replacement (on small motors). The commutator assembly on a large motor is a costly element, requiring precision assembly of many parts. On small motors, the commutator is usually permanently integrated into the rotor, so replacing it usually requires replacing the whole rotor.

Large brushes are desired for a larger brush contact area to maximize motor output, but small brushes are desired for low mass to maximize the speed at which the motor can run without the brushes excessively bouncing and sparking (comparable to the problem of "valve float" in internal combustion engines). (Small brushes are also desirable for lower cost.) Stiffer brush springs can also be used to make brushes of a given mass work at a higher speed, but at the cost of greater friction losses (lower efficiency) and accelerated brush and commutator wear. Therefore, DC motor brush design entails a trade-off between output power, speed, and efficiency/wear.



A: shunt
B: series
C: compound
f = field coil

There are five types of brushed DC motor:

A. DC shunt-wound motor

B. DC series-wound motor

C. DC compound motor (two configurations):

- Cumulative compound
- Differentially compounded

D. Permanent magnet DC motor (not shown)

E. Separately excited (sepex) (not shown).

Brushless DC motors

Some of the problems of the brushed DC motor are eliminated in the brushless design. In this motor, the mechanical "rotating switch" or commutator/brushgear assembly is replaced by an external electronic switch synchronised to the rotor's position. Brushless motors are typically 85–90% efficient or more (higher efficiency for a brushless electric motor of up to 96.5% were reported by researchers at the Tokai University in Japan in 2009), whereas DC motors with brushgear are typically 75–80% efficient.

Midway between ordinary DC motors and stepper motors lies the realm of the brushless DC motor. Built in a fashion very similar to stepper motors, these often use a permanent magnet external rotor, three phases of driving coils, one or more Hall effect sensors to sense the position of the rotor, and the associated drive electronics. The coils are activated, one phase after the other, by the drive electronics as cued by the signals from either Hall effect sensors or from the back EMF (electromotive force) of the undriven coils. In effect, they act as three-phase synchronous motors containing their own variable-frequency drive electronics. A specialized class of brushless DC motor controllers utilize EMF feedback through the main phase connections instead of Hall effect sensors to determine position and velocity. These motors are used extensively in electric radio-controlled vehicles. When configured with the magnets on the outside, these are referred to by modelers as outrunner motors.

Brushless DC motors are commonly used where precise speed control is necessary, as in computer disk drives or in video cassette recorders, the spindles within CD, CD-ROM (etc.) drives, and mechanisms within office products such as fans, laser printers and photocopiers. They have several advantages over conventional motors:

- Compared to AC fans using shaded-pole motors, they are very efficient, running much cooler than the equivalent AC motors. This cool operation leads to much-improved life of the fan's bearings.
- Without a commutator to wear out, the life of a DC brushless motor can be significantly longer compared to a DC motor using brushes and a commutator. Commutation also tends to cause a great deal of electrical and RF noise; without a commutator or brushes, a brushless motor may be used in electrically sensitive devices like audio equipment or computers.
- The same Hall effect sensors that provide the commutation can also provide a convenient tachometer signal for closed-loop control (servo-controlled) applications. In fans, the tachometer signal can be used to derive a "fan OK" signal.
- The motor can be easily synchronized to an internal or external clock, leading to precise speed control.
- Brushless motors have no chance of sparking, unlike brushed motors, making them better suited to environments with volatile chemicals and fuels. Also, sparking generates ozone which can accumulate in poorly ventilated buildings risking harm to occupants' health.
- Brushless motors are usually used in small equipment such as computers and are generally used to get rid of unwanted heat.
- They are also very quiet motors which is an advantage if being used in equipment that is affected by vibrations.

Modern DC brushless motors range in power from a fraction of a watt to many kilowatts. Larger brushless motors up to about 100 kW rating are used in electric vehicles. They also find significant use in high-performance electric model aircraft.

Coreless or ironless DC motors

Nothing in the principle of any of the motors described above requires that the iron (steel) portions of the rotor actually rotate. If the soft magnetic material of the rotor is made in the form of a cylinder, then (except for the effect of hysteresis) torque is exerted only on the windings of the electromagnets. Taking advantage of this fact is the **coreless or**

ironless DC motor, a specialized form of a brush or brushless DC motor. Optimized for rapid acceleration, these motors have a rotor that is constructed without any iron core. The rotor can take the form of a winding-filled cylinder, or a self-supporting structure comprising only the magnet wire and the bonding material. The rotor can fit inside the stator magnets; a magnetically soft stationary cylinder inside the rotor provides a return path for the stator magnetic flux. A second arrangement has the rotor winding basket surrounding the stator magnets. In that design, the rotor fits inside a magnetically soft cylinder that can serve as the housing for the motor, and likewise provides a return path for the flux.

Because the rotor is much lighter in weight (mass) than a conventional rotor formed from copper windings on steel laminations, the rotor can accelerate much more rapidly, often achieving a mechanical time constant under 1 ms. This is especially true if the windings use aluminum rather than the heavier copper. But because there is no metal mass in the rotor to act as a heat sink, even small coreless motors must often be cooled by forced air.

Related limited-travel actuators have no core and a bonded coil placed between the poles of high-flux thin permanent magnets. These are the fast head positioners for rigid-disk ("hard disk") drives.

Printed armature or pancake DC motors

A rather unusual motor design the pancake/printed armature motor has the windings shaped as a disc running between arrays of high-flux magnets, arranged in a circle, facing the rotor and forming an axial air gap. This design is commonly known the pancake motor because of its extremely flat profile, although the technology has had many brand names since its inception, such as ServoDisc.

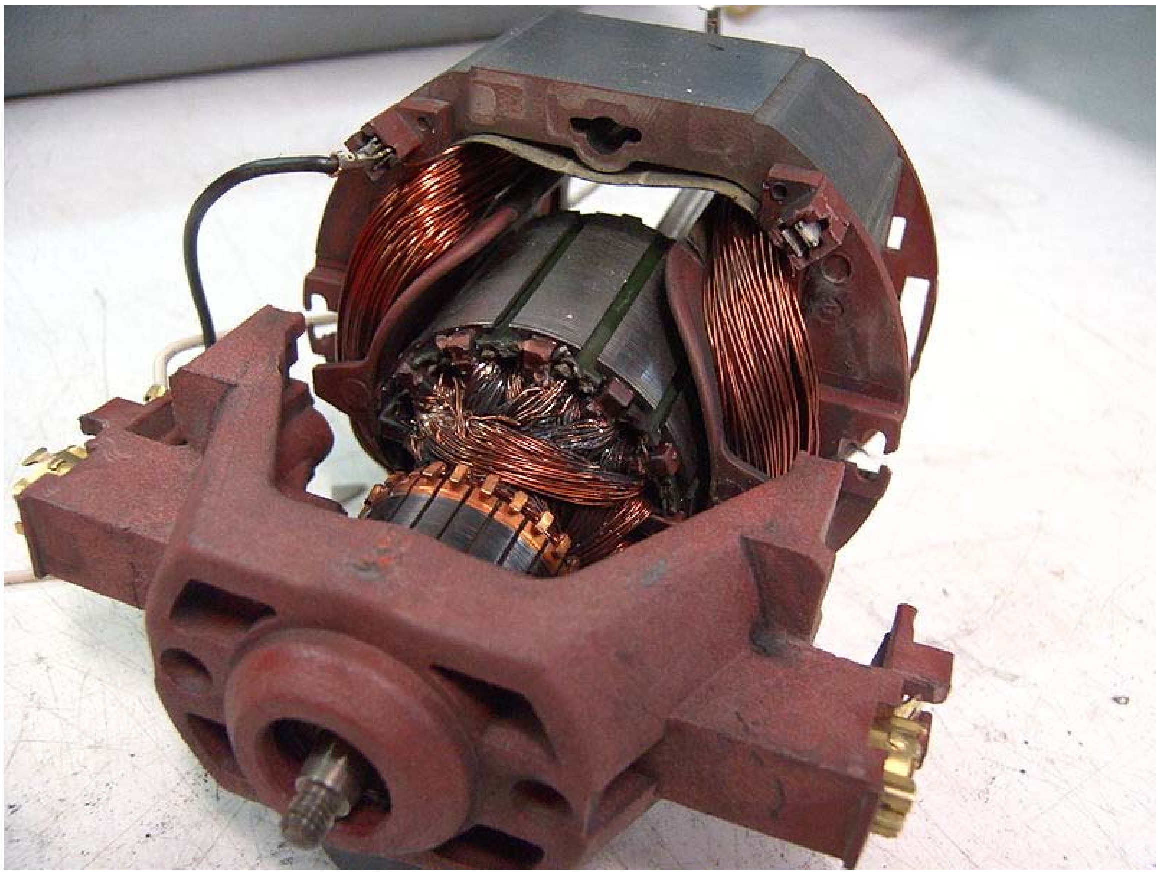
The printed armature (originally formed on a printed circuit board) in a printed armature motor is made from punched copper sheets that are laminated together using advanced composites to form a thin rigid disc. The printed armature has a unique construction, in the brushed motor world, in that it does not have a separate ring commutator. The brushes run directly on the armature surface making the whole design very compact.

An alternative manufacturing method is to use wound copper wire laid flat with a central conventional commutator, in a flower and petal shape. The windings are typically stabilized by being impregnated with electrical epoxy potting systems. These are filled epoxies that have moderate mixed viscosity and a long gel time. They are highlighted by low shrinkage and low exotherm, and are typically UL 1446 recognized as a potting compound for use up to 180°C (Class H) (UL File No. E 210549).

The unique advantage of ironless DC motors is that there is no cogging (vibration caused by attraction between the iron and the magnets) and parasitic eddy currents cannot form in the rotor as it is totally ironless. This can greatly improve efficiency, but variable-speed controllers must use a higher switching rate (>40 kHz) or direct current because of the decreased electromagnetic induction.

These motors were originally invented to drive the capstan(s) of magnetic tape drives, in the burgeoning computer industry. Pancake motors are still widely used in high-performance servo-controlled systems, humanoid robotic systems, industrial automation and medical devices. Due to the variety of constructions now available the technology is used in applications from high temperature military to low cost pump and basic servo applications.

Universal motors



Modern cheap universal motor, from a vacuum cleaner

A series-wound motor is referred to as a **universal motor** when it has been designed to operate on either AC or DC power. The ability to operate on AC is because the current in both the field and the armature (and hence the resultant magnetic fields) will alternate (reverse polarity) in synchronism, and hence the resulting mechanical force will occur in a constant direction.

Operating at normal power line frequencies, universal motors are often found in a range rarely larger than 1000 watt. Universal motors also form the basis of the traditional railway traction motor in electric railways. In this application, the use of AC to power a motor originally designed to run on DC would lead to efficiency losses due to eddy current heating of their magnetic components, particularly the motor field pole-pieces that, for DC, would have used solid (un-laminated) iron. Although the heating effects are reduced by using laminated pole-pieces, as used for the cores of transformers and by the use of laminations of high permeability electrical steel, one solution available at start of the 20th century was for the motors to be operated from very low frequency AC supplies, with 25 and 16.7 Hz operation being common. Because they used universal motors, locomotives using this design were also commonly capable of operating from a third rail powered by DC.

An advantage of the universal motor is that AC supplies may be used on motors which have some characteristics more common in DC motors, specifically high starting torque and very compact design if high running speeds are used. The negative aspect is the maintenance and short life problems caused by the commutator. Such motors are used in devices such as food mixers and power tools which are used only intermittently, and often have high starting-torque demands. Continuous speed control of a universal motor running on AC is easily obtained by use of a thyristor circuit, while multiple taps on the field coil provide (imprecise) stepped speed control. Household blenders that advertise many speeds frequently combine a field coil with several taps and a diode that can be inserted in series with the motor (causing the motor to run on half-wave rectified AC).

Induction motors can't turn faster than allowed by the power line frequency. By contrast, universal motors generally run at high speeds, making them useful for appliances such as blenders, vacuum cleaners, and hair dryers where high speed and light weight is desirable. They are also commonly used in portable power tools, such as drills, sanders, circular and jig saws, where the motor's characteristics work well. Many vacuum cleaner and weed trimmer motors exceed 10,000 RPM, while Dremel and other similar miniature grinders will often exceed 30,000 RPM.

Universal motors also lend themselves to electronic speed control and, as such, are an ideal choice for domestic washing machines. The motor can be used to agitate the drum (both forwards and in reverse) by switching the field winding with respect to the armature. The motor can also be run up to the high speeds required for the spin cycle.

Motor damage may occur from overspeeding (running at an rotational speed in excess of design limits) if the unit is operated with no significant load. On larger motors, sudden loss of load is to be avoided, and the possibility of such an occurrence is incorporated into the motor's protection and control schemes. In some smaller applications, a fan blade attached to the shaft often acts as an artificial load to limit the motor speed to a safe level, as well as a means to circulate cooling airflow over the armature and field windings.

AC motors

In 1882, Nikola Tesla discovered the rotating magnetic field, and pioneered the use of a rotary field of force to operate machines. He exploited the principle to design a unique two-phase induction motor in 1883. In 1885, Galileo Ferraris independently researched the concept. In 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin.

Tesla had suggested that the commutators from a machine could be removed and the device could operate on a rotary field of force. Professor Poeschel, his teacher, stated that would be akin to building a perpetual motion machine. Tesla would later attain U.S. Patent 0,416,194, *Electric Motor* (December 1889), which resembles the motor seen in many of Tesla's photos. This classic alternating current electro-magnetic motor was an induction motor.

Michail Osipovich Dolivo-Dobrovolsky later invented a three-phase "cage-rotor" in 1890. This type of motor is now used for the vast majority of commercial applications.

An AC motor has two parts. A stationary stator having coils supplied with AC current to produce a rotating magnetic field, and a rotor attached to the output shaft that is given a torque by the rotating field.

AC Motor with sliding rotor

Conical rotor brake motor incorporates the brake as an integral part of the conical sliding rotor. When the motor is at rest, a spring acts on the sliding rotor and forces the brake ring against the brake cap in the motor, holding the rotor stationary. When the motor is energized, its magnetic field generates both an axial and a radial component. The axial component overcomes the spring force, releasing the brake; while the radial component causes the rotor to turn. There is no additional brake control required.

Synchronous electric motor

A synchronous electric motor is an AC motor distinguished by a rotor spinning with coils passing magnets at the same rate as the alternating current and resulting magnetic field which drives it. Another way of saying this is that it has zero slip under usual operating conditions. Contrast this with an induction motor, which must slip to produce torque. A synchronous motor is like an induction motor except the rotor is excited by a DC field. Slip rings and brushes are used to conduct current to rotor. The rotor poles connect to each other and move at the same speed hence the name synchronous motor.

Induction motor

An induction motor is an asynchronous AC motor where power is transferred to the rotor by electromagnetic induction. An induction motor resembles a rotating transformer, because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Polyphase induction motors are widely used in industry.

Induction motors may be further divided into squirrel-cage motors and wound-rotor motors. Squirrel-cage motors have a heavy winding made up of solid bars, usually aluminum or copper, joined by rings at the ends of the rotor. Currents induced into this winding provide the rotor magnetic field. The shape of the rotor bars determines the speed-torque characteristics. At low speeds, the current induced in the squirrel cage is nearly at line frequency and tends to flow in the outer parts of the rotor cage. As the motor accelerates, the slip frequency becomes lower, and more current flows in the interior of the winding. By shaping the bars to change the resistance of the windings portions in the interior and outer parts of the cage, effectively a variable resistance is inserted in the rotor circuit.

In a wound-rotor motor, the rotor winding is made of many turns of insulated wire and is connected to slip rings on the motor shaft. An external resistor or other control devices can be connected in the rotor circuit. Resistors allow control of the motor speed, although significant power is dissipated in the external resistance. A converter can be fed from the rotor circuit and return the slip-frequency power that would otherwise be wasted back into the power system.

The wound-rotor induction motor is used primarily to start a high inertia load or a load that requires a very high starting torque across the full speed range. By correctly selecting the resistors used in the secondary resistance or slip ring starter, the motor is able to produce maximum torque at a relatively low supply current from zero speed to full speed. This type of motor also offers controllable speed.

Motor speed can be changed because the torque curve of the motor is effectively modified by the amount of resistance connected to the rotor circuit. Increasing the value of resistance will move the speed of maximum torque down. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs at zero speed, the torque will be further reduced.

When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. Reducing the load will cause the motor to speed up, and increasing the load will cause the motor to slow down until the load and motor torque are equal. Operated in this manner, the slip losses are dissipated in the secondary resistors and can be very significant. The speed regulation and net efficiency is also very poor.

Doubly-fed electric motor

Doubly-fed electric motors have two independent multiphase winding set, which contribute active (i.e., working) power to the energy conversion process, with at least one of the winding sets electronically controlled for variable speed operation. Two independent multiphase winding sets (i.e., dual armature) are the maximum provided in a single package without topology duplication. Doubly-fed electric motors are machines with an effective constant torque speed range that is twice synchronous speed for a given frequency of excitation. This is twice the constant torque speed range as singly-fed electric machines, which have only one active winding set.

A doubly-fed motor allows for a smaller electronic converter but the cost of the rotor winding and slip rings may offset the saving in the power electronics components. Difficulties with controlling speed near synchronous speed limit applications.

Singly-fed electric motor

Most AC motors are singly-fed. Singly-fed electric motors have a single multiphase winding set that is connected to a power supply. Singly-fed electric machines may be either induction or synchronous. The active winding set can be electronically controlled. Singly-fed electric machines have an effective constant torque speed range up to synchronous speed for a given excitation frequency.

Comparison of motor types

Comparison of motor types

Type	Advantages	Disadvantages	Typical Application	Typical Drive
AC polyphase induction squirrel-cage	Low cost, long life, high efficiency, large ratings available (to 1 MW or more), large number of standardized types	Starting inrush current can be high, speed control requires variable frequency source	Pumps, fans, blowers, conveyors, compressors	Poly-phase AC, variable frequency AC
Shaded-pole motor	Low cost Long life	Rotation slips from frequency Low starting torque Small ratings low efficiency	Fans, appliances, record players	Single phase AC
AC Induction (split-phase capacitor)	High power high starting torque	Rotation slips from frequency Starting switch required	Appliances Stationary Power Tools	Single phase AC
Universal motor	High starting torque, compact, high speed	Maintenance (brushes) lifespan Only small ratings economic	Drill, blender, vacuum cleaner, insulation blowers	Single phase AC or DC
AC Synchronous	Rotation in-sync with freq - hence no slip	More expensive	Industrial motors Clocks Audio turntables tape drives	Poly-phase AC
Stepper DC	Precision positioning High holding torque	High initial cost Requires a controller	Positioning in printers and floppy drives	DC
Brushless DC	Long lifespan	High initial cost	Hard drives	DC

	low maintenance High efficiency	Requires a controller	CD/DVD players electric vehicles	
Brushed DC	Simple speed control	Maintenance (brushes) Medium lifespan Costly commutator and brushes	Steel mills Paper making machines Treadmill exercisers automotive accessories	Direct DC or PWM
Pancake DC	Compact design Simple speed control	Medium cost Medium lifespan	Office Equip Fans/Pumps	Direct DC or PWM

Servo motor

A servomotor is used within a position-control or speed-control feedback control system. Servomotors are used in applications such as machine tools, pen plotters, and other control systems. Motors intended for use in a servomechanism must have well-documented characteristics for speed, torque, power. The dynamic response characteristics such as winding inductance and rotor inertia are also important; these factors limit the overall performance of the servomechanism loop. Large, powerful, but slow-responding servo loops may use conventional AC or DC motors and drive systems with position or speed feedback on the motor. As dynamic response requirements increase, more specialized motor designs such as coreless motors are used.

A servo system differs from some stepper motor applications in that the position feedback is continuous while the motor is running; a stepper system relies on the motor not to "miss steps" for short term accuracy, although a stepper system may include a "home" switch or other element to provide long-term stability of control.

Electrostatic motor

An electrostatic motor is based on the attraction and repulsion of electric charge. Usually, electrostatic motors are the dual of conventional coil-based motors. They typically require a high voltage power supply, although very small motors employ lower voltages. Conventional electric motors instead employ magnetic attraction and repulsion, and require high current at low voltages. In the 1750s, the first electrostatic motors were developed by Benjamin Franklin and Andrew Gordon. Today the electrostatic motor finds frequent use in micro-mechanical (MEMS) systems where their drive voltages are below 100 volts, and where moving, charged plates are far easier to fabricate than coils and iron cores. Also, the molecular machinery which runs living cells is often based on linear and rotary electrostatic motors.

Torque motors

A torque motor (also known as a limited torque motor) is a specialized form of induction motor which is capable of operating indefinitely while stalled, that is, with the rotor blocked from turning, without incurring damage. In this mode of operation, the motor will apply a steady torque to the load (hence the name).

A common application of a torque motor would be the supply- and take-up reel motors in a tape drive. In this application, driven from a low voltage, the characteristics of these motors allow a relatively constant light tension to be applied to the tape whether or not the capstan is feeding tape past the tape heads. Driven from a higher voltage, (and so delivering a higher torque), the torque motors can also achieve fast-forward and rewind operation without requiring any additional mechanics such as gears or clutches. In the computer gaming world, torque motors are used in force feedback steering wheels.

Another common application is the control of the throttle of an internal combustion engine in conjunction with an electronic governor. In this usage, the motor works against a return spring to move the throttle in accordance with the output of the governor. The latter monitors engine speed by counting electrical pulses from the ignition system or from a magnetic pickup and, depending on the speed, makes small adjustments to the amount of current applied to the motor. If the engine starts to slow down relative to the desired speed, the current will be increased, the motor will develop more torque, pulling against the return spring and opening the throttle. Should the engine run too fast, the governor will reduce the current being applied to the motor, causing the return spring to pull back and close the throttle.

Stepper motors

Closely related in design to three-phase AC synchronous motors are stepper motors, where an internal rotor containing permanent magnets or a magnetically soft rotor with salient poles is controlled by a set of external magnets that are switched electronically. A stepper motor may also be thought of as a cross between a DC electric motor and a rotary solenoid. As each coil is energized in turn, the rotor aligns itself with the magnetic field produced by the energized field winding. Unlike a synchronous motor, in its application, the stepper motor may not rotate continuously; instead, it "steps" — starts and then quickly stops again — from one position to the next as field windings are energized and de-energized in sequence. Depending on the sequence, the rotor may turn forwards or backwards, and it may change direction, stop, speed up or slow down arbitrarily at any time.

Simple stepper motor drivers entirely energize or entirely de-energize the field windings, leading the rotor to "cog" to a limited number of positions; more sophisticated drivers can proportionally control the power to the field windings, allowing the rotors to position between the cog points and thereby rotate extremely smoothly. This mode of operation is often called microstepping. Computer controlled stepper motors are one of the most versatile forms of positioning systems, particularly when part of a digital servo-controlled system.

Stepper motors can be rotated to a specific angle in discrete steps with ease, and hence stepper motors are used for read/write head positioning in computer floppy diskette drives. They were used for the same purpose in pre-gigabyte era computer disk drives, where the precision and speed they offered was adequate for the correct positioning of the read/write head of a hard disk drive. As drive density increased, the precision and speed limitations of stepper motors made them obsolete for hard drives—the precision limitation made them unusable, and the speed limitation made them uncompetitive—thus newer hard disk drives use voice coil-based head actuator systems. (The term "voice coil" in this connection is historic; it refers to the structure in a typical (cone type) loudspeaker. This structure was used for a while to position the heads. Modern drives have a pivoted coil mount; the coil swings back and forth, something like a blade of a rotating fan. Nevertheless, like a voice coil, modern actuator coil conductors (the magnet wire) move perpendicular to the magnetic lines of force.)

Stepper motors were and still are often used in computer printers, optical scanners, and digital photocopiers to move the optical scanning element, the print head carriage (of dot matrix and inkjet printers), and the platen. Likewise, many computer plotters (which since the early 1990s have been replaced with large-format inkjet and laser printers) used rotary stepper motors for pen and platen movement; the typical alternatives here were either linear stepper motors or servomotors with complex closed-loop control systems.

So-called quartz analog wristwatches contain the smallest commonplace stepping motors; they have one coil, draw very little power, and have a permanent-magnet rotor. The same kind of motor drives battery-powered quartz clocks. Some of these watches, such as chronographs, contain more than one stepping motor.

Stepper motors were upscaled to be used in electric vehicles under the term SRM (Switched Reluctance Motor).

Linear motors

A linear motor is essentially an electric motor that has been "unrolled" so that, instead of producing a torque (rotation), it produces a straight-line force along its length by setting up a traveling electromagnetic field.

Linear motors are most commonly induction motors or stepper motors. You can find a linear motor in a maglev (Transrapid) train, where the train "flies" over the ground, and in many roller-coasters where the rapid motion of the motorless railcar is controlled by the rail. On a smaller scale, at least one letter-size (8.5" x 11") computer graphics X-Y pen plotter made by Hewlett-Packard (in the late 1970s to mid 1980's) used two linear stepper motors to move the pen along the two orthogonal axes.

Nanotube nanomotor

Researchers at University of California, Berkeley, recently developed rotational bearings based upon multiwall carbon nanotubes. By attaching a gold plate (with dimensions of the order of 100 nm) to the outer shell of a suspended multiwall carbon nanotube (like nested carbon cylinders), they are able to electrostatically rotate the outer shell relative to the inner core. These bearings are very robust; devices have been oscillated thousands of times with no indication of wear. These nanoelectromechanical systems (NEMS) are the next step in miniaturization and may find their way into commercial applications in the future.

Spacecraft propulsive motors

An **electrically powered spacecraft propulsion** system is any of a number of forms of electric motors which spacecraft can employ to gain mechanical energy in outer space. Most of these kinds of spacecraft propulsion work by electrically powering propellant to high speed, but electrodynamic tethers work by interacting with a planet's magnetosphere.

Energy conversion by an electric motor

Using mathematical models in terms of a magnetic dipole, Ribarič and Šušteršič consider how in the case of the synchronous motor and induction motor an external source is supplying electrical energy to the stator so as to maintain its revolving magnetic field; this energy is then transmitted by the revolving magnetic field to the magnetic dipole of the rotor; there it is converted into mechanical energy, and transmitted mechanically by the rotating shaft to an external user. On the other hand, in the case of a commutator motor, the external source delivers electrical energy directly to the rotor magnetic dipole for conversion into mechanical energy.

Power

The power output of a rotary electric motor is:

$$P = \frac{rpm \times T}{5252}$$

Where P is in horsepower, rpm is the shaft speed in revolutions per minute and T is the torque in foot pounds.

And for a linear motor:

$$P = F \times v$$

Where P is the power in watts, and F is in Newtons and v is the speed in metres per second.

Efficiency

To calculate a motor's efficiency, the mechanical output power is divided by the electrical input power:

$$\eta = \frac{P_m}{P_e},$$

where η is energy conversion efficiency, P_e is electrical input power, and P_m is mechanical output power.

In simplest case $P_e = VI$, and $P_m = T\omega$, where V is input voltage, I is input current, T is output torque, and ω is output angular velocity. It is possible to derive analytically the point of maximum efficiency. It is typically at less than 1/2 the stall torque.

Goodness factor

Professor Eric Laithwaite proposed a metric to determine the 'goodness' of an electric motor:

$$G = \frac{\omega}{resistance \times reluctance} = \frac{\omega \mu \sigma A_m A_e}{l_m l_e}$$

Where:

G is the goodness factor (factors above 1 are likely to be efficient)
A_m,A_e are the cross sections of the magnetic and electric circuit
l_m,l_e are the lengths of the magnetic and electric circuits
μ is the permeability of the core
ω is the angular frequency the motor is driven at

From this he showed that the most efficient motors are likely to be relatively large. However, the equation only directly relates to non permanent magnet motors.

Torque capability of motor types

When optimally designed within a given core saturation constraint and for a given active current (i.e., torque current), voltage, pole-pair number, excitation frequency (i.e., synchronous speed), and air-gap flux density, all categories of electric motors or generators will exhibit virtually the same maximum continuous shaft torque (i.e., operating torque) within a given air-gap area with winding slots and back-iron depth, which determines the physical size of electromagnetic core. Some applications require bursts of torque beyond the maximum operating torque, such as short bursts of torque to accelerate an electric vehicle from standstill. Always limited by magnetic core saturation or safe operating temperature rise and voltage, the capacity for torque bursts beyond the maximum operating torque differs significantly between categories of electric motors or generators.

Capacity for bursts of torque should not be confused with field weakening capability inherent in fully electromagnetic electric machines (Permanent Magnet (PM) electric machine are excluded). Field weakening, which is not available with PM electric machines, allows an electric machine to operate beyond the designed frequency of excitation.

Electric machines without a transformer circuit topology, such as Field-Wound (i.e., electromagnet) or Permanent Magnet (PM) Synchronous electric machines cannot realize bursts of torque higher than the maximum designed torque without saturating the magnetic core and rendering any increase in current as useless. Furthermore, the permanent magnet assembly of PM synchronous electric machines can be irreparably damaged, if bursts of torque exceeding the maximum operating torque rating are attempted.

Electric machines with a transformer circuit topology, such as Induction (i.e., asynchronous) electric machines, Induction Doubly-Fed electric machines, and Induction or Synchronous Wound-Rotor Doubly-Fed (WRDF) electric machines, exhibit very high bursts of torque because the active current (i.e., Magneto-Motive-Force or the product of current and winding-turns) induced on either side of the transformer oppose each other and as a result, the active current contributes nothing to the transformer coupled magnetic core flux density, which would otherwise lead to core saturation.

Electric machines that rely on Induction or Asynchronous principles short-circuit one port of the transformer circuit and as a result, the reactive impedance of the transformer circuit becomes dominant as slip increases, which limits the magnitude of active (i.e., real) current. Still, bursts of torque that are two to three times higher than the maximum design torque are realizable.

The Synchronous WRDF electric machine is the only electric machine with a truly dual ported transformer circuit topology (i.e., both ports independently excited with no short-circuited port). The dual ported transformer circuit topology is known to be unstable and requires a multiphase slip-ring-brush assembly to propagate limited power to the rotor winding set. If a precision means were available to instantaneously control torque angle and slip for synchronous operation during motoring or generating while simultaneously providing brushless power to the rotor winding set, the active current of the Synchronous WRDF electric machine would be independent of the reactive impedance of the transformer circuit and bursts of torque significantly higher than the maximum operating torque and far beyond the practical capability of any other type of electric machine would be realizable. Torque bursts greater than eight times operating torque have been calculated.

Continuous Torque Density

The continuous torque density of conventional electric machines is determined by the size of the air-gap area and the back-iron depth, which are determined by the power rating of the armature winding set, the speed of the machine, and the achievable air-gap flux density before core saturation. Despite the high coercivity of neodymium or samarium-cobalt permanent magnets, continuous torque density is virtually the same amongst electric machines with optimally designed armature winding sets. Continuous torque density should never be confused with peak torque density, which comes with the manufacturer's chosen method of cooling, which is available to all, or period of operation before destruction by overheating of windings or even permanent magnet damage.

Continuous Power Density

The continuous power density is determined by the product of the continuous torque density and the constant torque speed range of the electric machine.

Motor standards

The following are major design and manufacturing standards covering electric motors:

- International Electrotechnical Commission: IEC 60034 Rotating Electrical Machines
- National Electrical Manufacturers Association (USA): NEMA MG 1 Motors and Generators
- Underwriters Laboratories (USA): UL 1004 - Standard for Electric Motors

Uses

Electric motors are used in many, if not most, modern machines. Obvious uses would be in rotating machines such as fans, turbines, drills, the wheels on electric cars, locomotives and conveyor belts. Also, in many vibrating or oscillating machines, an electric motor spins an irregular figure with more area on one side of the axle than the other, causing it to appear to be moving up and down.

Electric motors are also popular in robotics. They are used to turn the wheels of vehicular robots, and servo motors are used to turn arms and legs in humanoid robots. In flying robots, along with helicopters, a motor causes a propeller or wide, flat blades to spin and create lift force, allowing vertical motion.

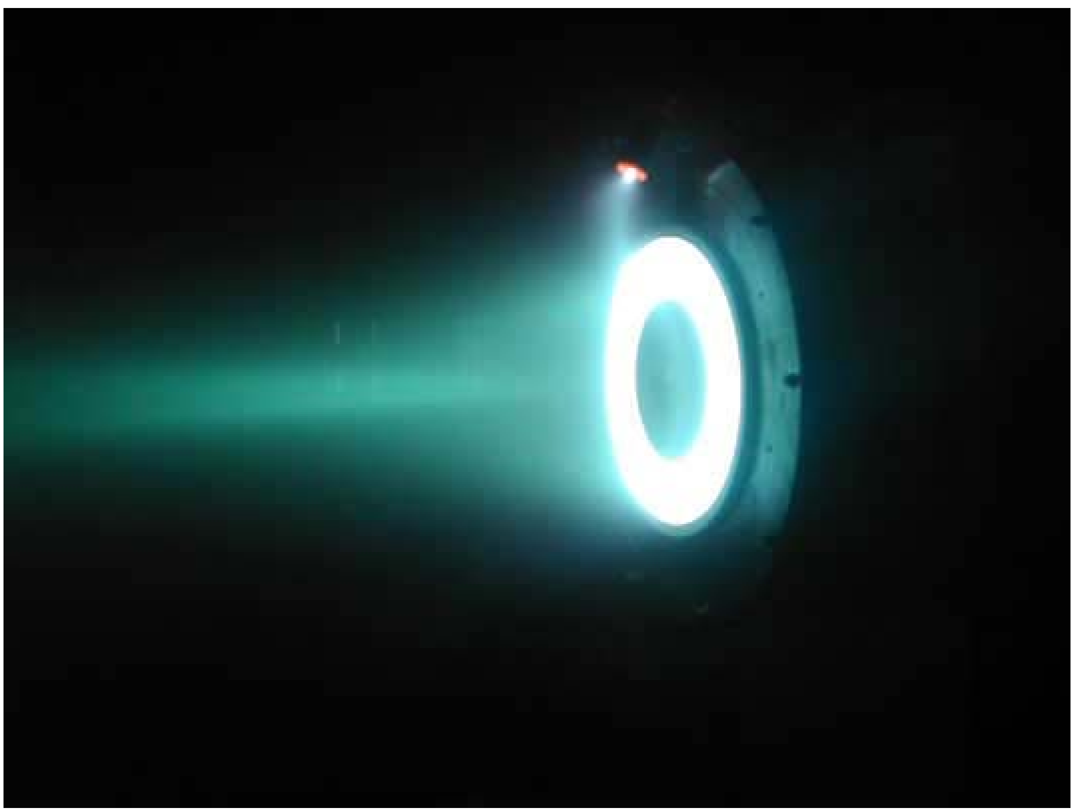
Electric motors are replacing hydraulic cylinders in airplanes and military equipment.

In industrial and manufacturing businesses, electric motors are used to turn saws and blades in cutting and slicing processes, and to spin gears and mixers (the latter very common in food manufacturing). Linear motors are often used to push products into containers horizontally.

Many kitchen appliances also use electric motors. Food processors and grinders spin blades to chop and break up foods. Blenders use electric motors to mix liquids, and microwave ovens use motors to turn the tray food sits on. Toaster ovens also use electric motors to turn a conveyor to move food over heating elements.

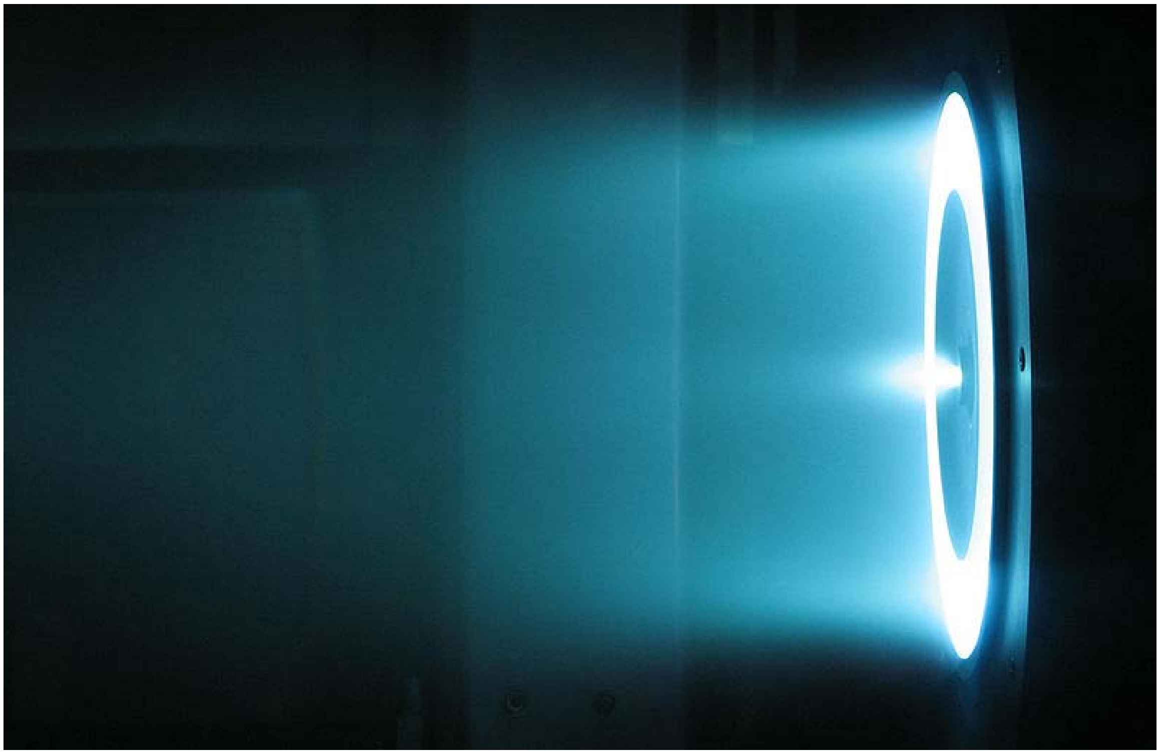
Chapter 6

Hall Effect Thruster



2 kW Hall thruster in operation as part of the Hall Thruster Experiment at the Princeton Plasma Physics Laboratory.

In spacecraft propulsion, a **Hall thruster** is a type of ion thruster in which the propellant is accelerated by an electric field. Hall thrusters trap electrons in a magnetic field and then use the electrons to ionize propellant, efficiently accelerate the ions to produce thrust, and neutralize the ions in the plume. Hall thrusters are sometimes referred to as **Hall Effect Thrusters** or **Hall Current Thrusters**.



6 kW Hall thruster in operation at the NASA Jet Propulsion Laboratory.

Hall thrusters operate on a variety of propellants, the most common being xenon. Other propellants of interest include krypton, argon, bismuth, magnesium, and zinc.

Hall thrusters are able to accelerate their exhaust to speeds between 10–80 km/s (1000-8000 s specific impulse), with most models operating between 15–30 km/s (1500-3000 s specific impulse). The thrust produced by a Hall thruster varies depending on the power level. Devices operating at 1.35 kW produce about 83 mN of thrust. High power models have demonstrated up to 3 N in the laboratory. Power levels up to 100 kW have been demonstrated by xenon Hall thrusters.

History

Hall thrusters were studied independently in the US and the USSR in the 1950s and 1960s. However, the Hall thruster was only developed into an efficient propulsion device in the former Soviet Union, whereas in the US, scientists focused instead on developing gridded ion thrusters.

Two types of Hall thrusters were developed in the Soviet Union:

- thrusters with wide acceleration zone, SPT (Russian: **СПД**, **с**тационарный **п**лазменный **д**вигатель; English: ***SPT***, **S**tationary **P**lasma **T**hruster) at Design Bureau Fakel
- thrusters with narrow acceleration zone, DAS (Russian: **ДАС**, **д**вигатель с **а**нодным **с**лоем; English: **TAL**, **T**hruster with **A**node **L**ayer), at the Central Research Institute for Machine Building (TsNIIMASH).

Soviet and Russian SPT thrusters

The common SPT design was largely the work of A. I. Morozov. The first SPT to operate in space, an SPT-50 launched on the Soviet Meteor spacecraft, was launched December 1971. They were mainly used for satellite stabilization in North-South and in East-West directions. Since then until the late 1990s 118 SPT engines completed their mission and some 50 continued to be operated. Thrust of the first generation of SPT engines, SPT-50 and SPT-60 was 20 and 30 mN respectively. In 1982 SPT-70 and SPT-100 were introduced, their thrusts being 40 and 83 mN, respectively. In the post-Soviet Russia high-power (a few kilowatts) SPT-140, SPT-160, SPT-200, T-160 and low-power (less than 500 W) SPT-35 were introduced.

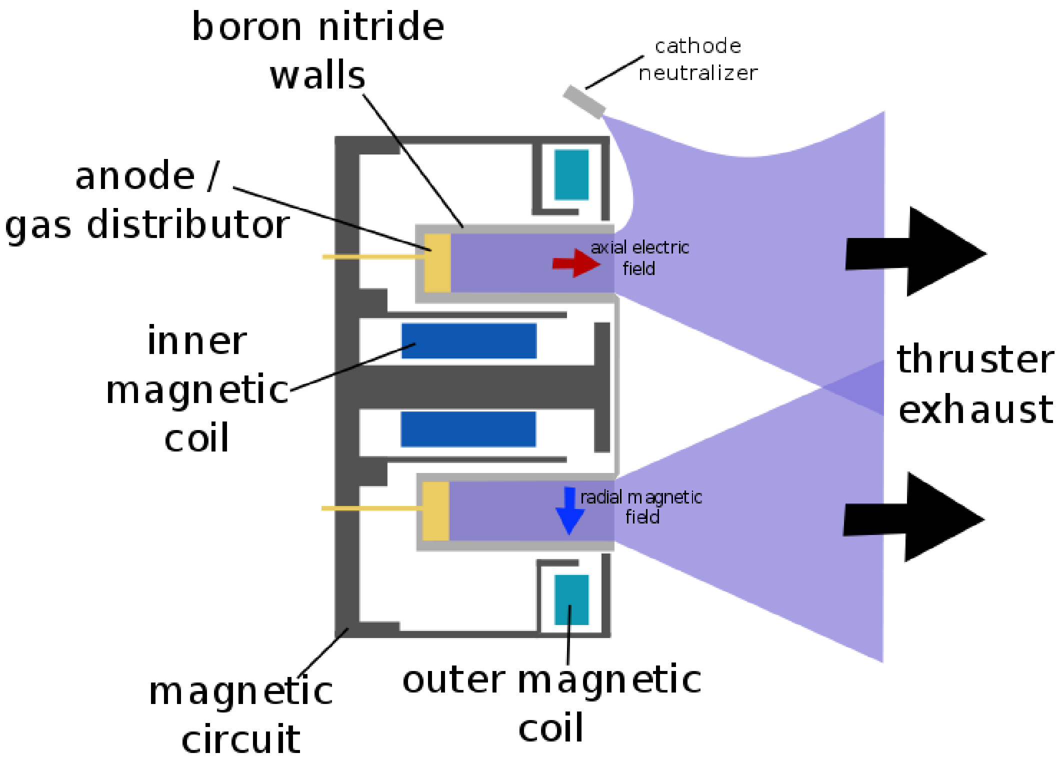
Soviet and Russian TAL-type thrusters include the D-38, D-55, D-80, and D-100.

Soviet-built thrusters were introduced to the West in 1992 after a team of electric propulsion specialists from NASA's Jet Propulsion Laboratory, Glenn Research Center, and the Air Force Research Laboratory, under the support of the Ballistic Missile Defense Organization, visited Soviet laboratories and experimentally evaluated the SPT-100 (i.e., a 100 mm diameter SPT thruster). Over 200 Hall thrusters have been flown on Soviet/Russian satellites in the past thirty years. No failures of a Hall thruster has ever occurred on orbit. Hall thruster continue to be used on Russian spacecraft and have also flown on European and American spacecraft. Space Systems/Loral, an American commercial satellite manufacturer, now flies Fakel SPT-100's on their GEO communications spacecraft. Since their introduction to the west in the early 1990s, Hall thrusters have been the subject of a large number of research efforts throughout the United States, France, Italy, Japan, and Russia (with many smaller efforts scattered in various countries across the globe). Hall thruster research in the US is conducted at several government laboratories, universities and private companies. Government centers include NASA's Jet Propulsion Laboratory, NASA's Glenn Research Center and the Air Force Research Laboratory (Edwards AFB, CA). Universities include the University of Michigan, Stanford, MIT, Princeton, Michigan Tech, and Georgia Tech. A considerable amount of development is being conducted in industry, such as Aerojet and Busek Co. in the USA, SNECMA in France and Alta in Italy.

The first use of Hall thrusters outside of Earth's orbit was on the European Space Agency (ESA) lunar mission SMART-1 in 2003. Hall thrusters were first demonstrated on a western satellite on the Naval Research Laboratory (NRL) STEX spacecraft, which flew the Russian D-55. The first American Hall thruster to fly in space was the Busek BHT-200 on TacSat-2 technology demonstration spacecraft. The first flight of an American Hall thruster on an operational mission, was the Aerojet BPT-4000, which launched August 2010 on the military Advanced Extremely High Frequency GEO communications satellite. At 4.5 kW, the BPT-4000 is also the highest power Hall thruster ever flown in space. Besides the usual stationkeeping tasks, the BPT-4000 is also providing orbit raising capability to the spacecraft. Several countries worldwide continue efforts to qualify Hall thruster technology for commercial uses.

Operation

The essential working principle of the Hall thruster is that it uses an electrostatic potential to accelerate ions up to high speeds. In a Hall thruster the attractive negative charge is provided by an electron plasma at the open end of the thruster instead of a grid. A radial magnetic field of a hundred gauss (about 100-300 G) is used to confine the electrons, where the combination of the radial magnetic field and axial electric field cause the electrons to drift azimuthally, forming the Hall current from which the device gets its name.



Hall Thruster. Hall thrusters are largely axially symmetric. This is a cross-section containing that axis.

A schematic of a Hall thruster is shown in the image to the right. An electric potential between 150-800 Volts is applied between the anode and cathode.

The central spike forms one pole of an electromagnet and is surrounded by an annular space and around that is the other pole of the electromagnet, with a radial magnetic field in-between.

The propellant, such as xenon gas is fed through the anode, which has numerous small holes in it to act as a gas distributor. Xenon propellant is used because of its high molecular weight and low ionization potential. As the neutral xenon atoms diffuse into the channel of the thruster, they are ionized by collisions with high energy circulating electrons (typically 10-40 eV, or about 10% of the discharge voltage). Once ionized, the xenon ions typically have a charge of +1 though a small fraction (~20%) are +2.

The xenon ions are then accelerated by the electric field between the anode and the cathode. For discharge voltages of 300 V, the ions reach speeds of around 15,000 m/s for a specific impulse of 1,500 seconds (15 kN·s/kg). Upon exiting however, the ions pull an equal number of electrons with them, creating a plume with no net charge.

The radial magnetic field is designed to be strong enough to substantially deflect the low-mass electrons, but not the high-mass ions which have a much larger gyroradius and are hardly impeded. The majority of electrons are thus stuck orbiting in the region of high radial magnetic field near the thruster exit plane, trapped in $\boldsymbol{E}\times\boldsymbol{B}$ (axial electric field and radial magnetic field). This orbital rotation of the electrons is a circulating Hall current and it is from this that the Hall thruster gets its name. Collisions with other particles and walls as well as plasma instabilities allow some of the electrons to be freed from the magnetic field and they drift towards the anode.

About 20-30% of the discharge current is an electron current which does not produce thrust, which limits the energetic efficiency of the thruster; the other 70-80% of the current is in the ions. Because the majority of electrons are trapped in the Hall current, they have a long residence time inside the thruster and are able to ionize almost all of the xenon propellant, allowing for mass utilizations of 90-99%. The mass utilization efficiency of the thruster is thus around 90%, while the discharge current efficiency is around 70% for a combined thruster efficiency of around 63% (= 90% × 70%). Modern Hall thrusters have achieved efficiencies as high as 75% through advanced designs.

Compared to chemical rockets the thrust is very small, on the order of 83 mN for a typical thruster operating at 300 V, 1.5 kW. For comparison, the weight of a coin like the U.S. quarter or a 20-cent Euro coin is approximately 60 mN.

However, Hall thrusters operate at the high specific impulses that is typical of electric propulsion. One particular advantage of Hall thrusters, as compared to a gridded ion thruster, is that the generation and acceleration of the ions takes place in a quasi-neutral plasma and so there is no Child-Langmuir charge (space charge) saturated current limitation on the thrust density. This allows for much smaller thrusters compared to gridded ion thrusters.

Another advantage is that these thrusters can use a wider variety of propellants supplied to the anode, even oxygen, although something easily ionized is needed at the cathode.

Applications

Hall thrusters have been flying in space since December 1971 when the Soviets launched an SPT-50 on the Meteor satellite. Over 240 thrusters have flown in space since that time with a 100% success rate. Hall thrusters are now routinely flown on commercial GEO communications satellite where they are used for orbit insertion and stationkeeping.

On October 23, 1998, the first Hall thruster to fly on a western satellite was the Russian D-55 built by TsNIIMASH on the NRO's STEX spacecraft. On September 28, 2003, the first Hall thruster used outside of geosynchronous Earth orbit began as the European

Space Agency's SMART-1 spacecraft started its journey to the moon using a Snecma PPS-1350.

The solar electric propulsion system of the European Space Agency's SMART-1 spacecraft used a Snecma PPS-1350-G Hall thruster. SMART-1 was a technology demonstration mission that orbited the moon. The use of the PPS-1350-G was the first use of a Hall thruster outside of geosynchronous earth orbit (GEO). Unlike most Hall thruster propulsion systems used in commercial applications, the Hall thruster on SMART-1 could be throttled over a range of power, specific impulse, and thrust:

- Discharge Power: 0.46-1.19 kW
- Specific Impulse: 1100–1600 s
- Thrust: 30-70 mN

In 2005, SMART-1 exhausted its xenon supply after flawlessly operating the thruster and establishing new records for Hall thruster operation in space

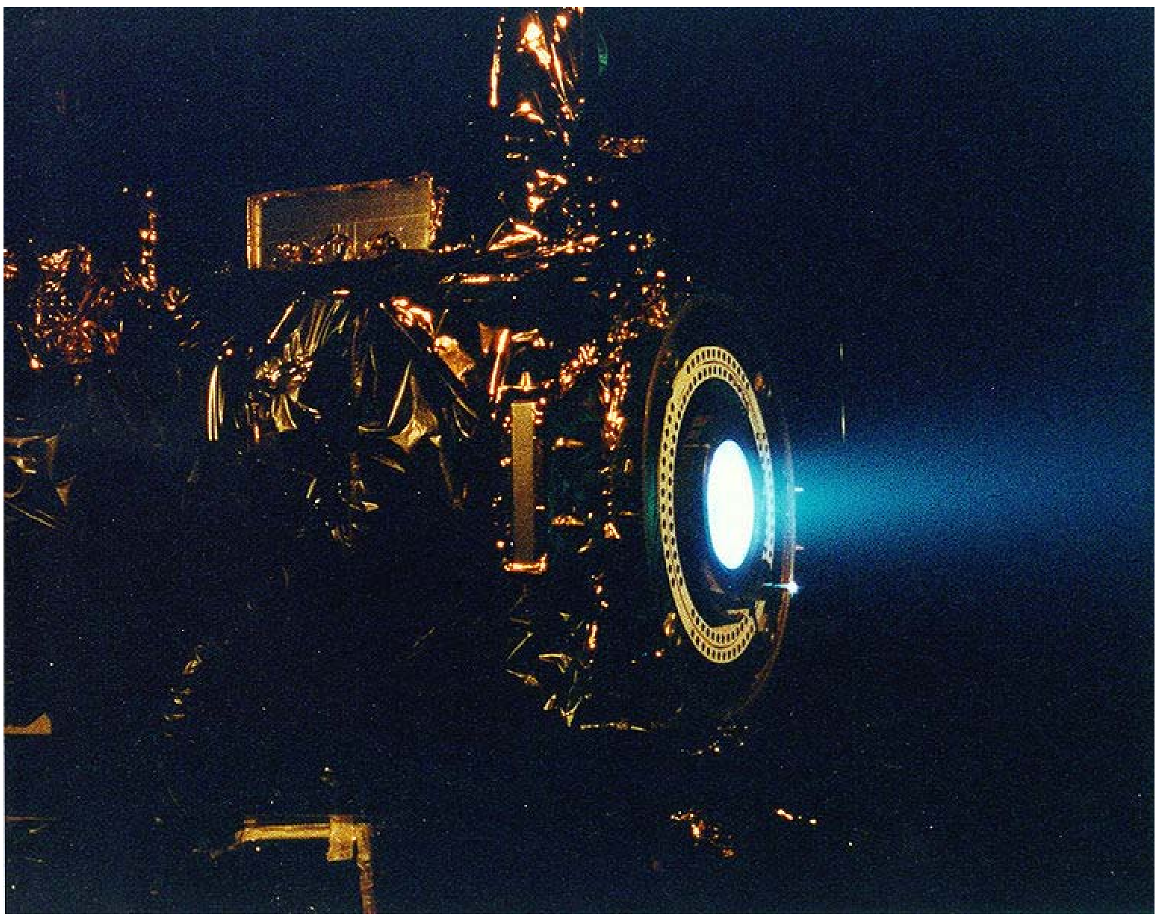
- Thruster operating time: 5000 h
- Xenon throughput: 82 kg
- Total Impulse: 1.1 MN-s
- Total ΔV: 3.9 km/s

In parallel to the flight demonstration, a qualification model (QM) PPS-1350-G has also undergone wear testing on the ground. Through 2007, the QM model has demonstrated:

- Thruster operating time: 10,500 h
- Total impulse: 3.39 MN-s
- Start/Stop Cycles: 7309

Chapter 7

Ion Thruster



NASA's 2.3 kW NSTAR ion thruster during a hot fire test at the Jet Propulsion Laboratory on the Deep Space 1 spacecraft.

An **ion thruster** is a form of electric propulsion used for spacecraft propulsion that creates thrust by accelerating ions. Ion thrusters are categorized by how they accelerate the ions, using either electrostatic or electromagnetic force. Electrostatic ion thrusters use the Coulomb force and accelerate the ions in the direction of the electric field. Electromagnetic ion thrusters use the Lorentz force to accelerate the ions. The term "ion thruster" by itself usually denotes the electrostatic or gridded ion thrusters.

The thrust created in ion thrusters is very small compared to conventional chemical rockets, but a very high specific impulse, or propellant efficiency, is obtained. This high propellant efficiency is achieved through the very frugal propellant consumption of the ion thruster propulsion system. They do, however, use a large amount of power, and in use their performance is power limited (whereas normal chemical thrusters are energy limited). Given the practical weight of suitable power sources, the accelerations given by these types of thrusters is of the order of one thousandth of standard gravity.

Due to their relatively high power needs, given the specific power of power supplies, and the requirement of an environment void of other ionized particles, ion thrust propulsion is currently only practical beyond planetary atmosphere (in space).

Origins

The official father of the concept of electric propulsion is Konstantin Tsiolkovsky as he is the first to publish mention of the idea in 1911. However, the first documented instance where the possibility of electric propulsion is considered is found in Robert H. Goddard's handwritten notebook in an entry dated 6 September 1906. The first experiments with ion thrusters were carried out by Goddard at Clark University from 1916–1917. The technique was recommended for near-vacuum conditions at high altitude, but thrust was demonstrated with ionized air streams at atmospheric pressure. The idea appeared again in Hermann Oberth's "Wege zur Raumschiffahrt” (Ways to Spaceflight), published in 1923, where he explained his thoughts on the mass savings of electric propulsion, predicted its use in spacecraft propulsion and attitude control, and advocated electrostatic acceleration of charged gases.

A working ion thruster was built by Harold R. Kaufman in 1959 at the NASA Glenn Research Center facilities. It was similar to the general design of a gridded electrostatic ion thruster with mercury as its fuel. Suborbital tests of the engine followed during the 1960s and in 1964 the engine was sent into a suborbital flight aboard the Space Electric Rocket Test 1 (SERT 1). It successfully operated for the planned 31 minutes before falling back to Earth.

Soviet and Russian Hall effect thrusters

The Hall effect thruster was studied independently in the U.S. and the USSR in the 1950s and 60s. However, the concept of a Hall thruster was only developed into an efficient propulsion device in the former Soviet Union, whereas in the U.S., scientists focused instead on developing gridded ion thrusters. Hall effect thrusters were operated on Soviet satellites since 1972. Until the 1990s they were mainly used for satellite stabilization in North-South and in East-West directions. Some 100-200 engines completed their mission on Soviet and Russian satellites until the late 1990s. Soviet thruster design was introduced to the West in 1992 after a team of electric propulsion specialists, under the support of the Ballistic Missile Defense Organization, visited Soviet laboratories.

General description

Ion thrusters use beams of ions (electrically charged atoms or molecules) to create thrust in accordance with momentum conservation. The method of accelerating the ions varies, but all designs take advantage of the charge/mass ratio of the ions. This ratio means that relatively small potential differences can create very high exhaust velocities. This reduces the amount of reaction mass or fuel required, but increases the amount of specific power required compared to chemical rockets. Ion thrusters are therefore able to achieve extremely high specific impulses. The drawback of the low thrust is low spacecraft acceleration because the mass of current electric power units is directly correlated with the amount of power given. This low thrust makes ion thrusters unsuited for launching spacecraft into orbit, but they are ideal for in-space propulsion applications.

Various ion thrusters have been designed and they all generally fit under two categories. The thrusters are categorized as either electrostatic or electromagnetic. The main difference is how the ions are accelerated.

- Electrostatic ion thrusters use the Coulomb force and are categorized as accelerating the ions in the direction of the electric field.
- Electromagnetic ion thrusters use the Lorentz force to accelerate the ions.

Power supplies for ion thrusters are usually solar panels, but at sufficiently large distances from the Sun, nuclear power is used. In each case the power supply mass is essentially proportional to the peak power that can be supplied, and they both essentially give, for this application, no limit to the energy.

Electrostatic ion thrusters

Gridded electrostatic ion thrusters

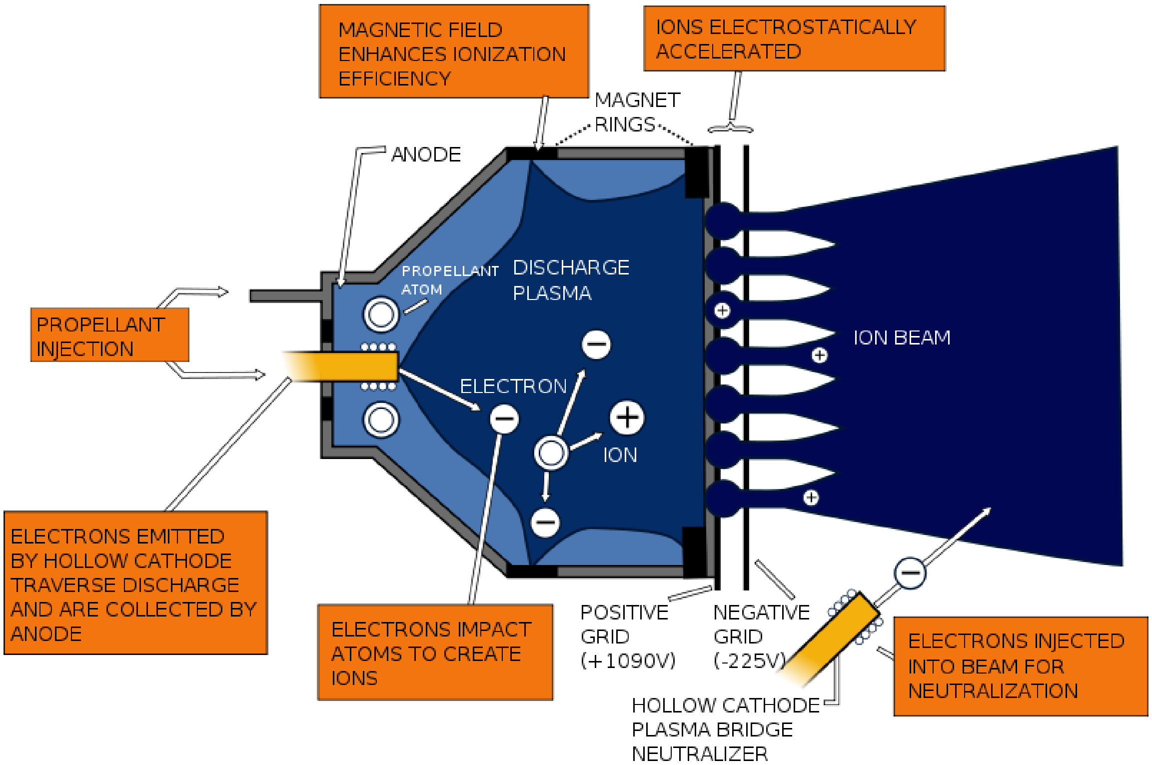


Figure 2: A diagram of how a gridded electrostatic ion engine (Kaufman type) works

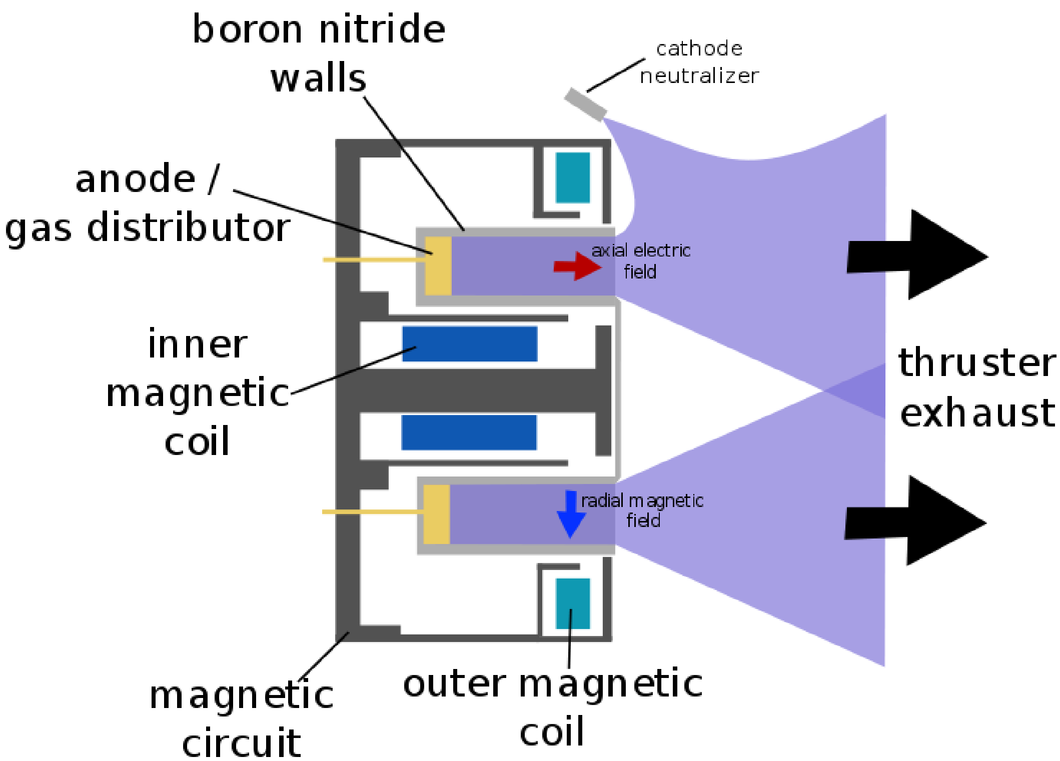
Gridded electrostatic ion thrusters commonly utilize xenon gas. This gas has no charge and is ionized by bombarding it with energetic electrons. These electrons can be provided from a hot cathode filament and accelerated in the electrical field of the cathode fall to the anode (Kaufman type ion thruster). Alternatively, the electrons can be accelerated by the oscillating electric field induced by an alternating magnetic field of a coil, which results in a self-sustaining discharge and omits any cathode (radiofrequency ion thruster).

The positively charged ions are extracted by an extraction system consisting of 2 or 3 multi-aperture grids. After entering the grid system via the plasma sheath the ions are accelerated due to the potential difference between the first and second grid (named screen and accelerator grid) to the final ion energy of typically 1-2 keV, thereby generating the thrust.

Ion thrusters emit a beam of positive charged xenon ions only. In order to avoid charging-up the spacecraft, another cathode is placed near the engine, which emits electrons (basically the electron current is the same as the ion current) into the ion beam. This also prevents the beam of ions from returning to the spacecraft and thereby cancelling the thrust.

Gridded electrostatic ion thruster research (past/present):

- NASA Solar electric propulsion Technology Application Readiness (NSTAR)
- NASA's Evolutionary Xenon Thruster (NEXT)
- Nuclear Electric Xenon Ion System (NEXIS)
- High Power Electric Propulsion (HiPEP)
- EADS Radio-Frequency Ion Thruster (RIT)
- Dual-Stage 4-Grid (DS4G)



Schematic of a Hall Thruster

Hall effect thrusters

Hall effect thrusters accelerate ions with the use of an electric potential maintained between a cylindrical anode and a negatively charged plasma which forms the cathode. The bulk of the propellant (typically xenon gas) is introduced near the anode, where it becomes ionized, and the ions are attracted towards the cathode, they accelerate towards and through it, picking up electrons as they leave to neutralize the beam and leave the thruster at high velocity.

The anode is at one end of a cylindrical tube, and in the center is a spike which is wound to produce a radial magnetic field between it and the surrounding tube. The ions are largely unaffected by the magnetic field, since they are too massive. However, the electrons produced near the end of the spike to create the cathode are far more affected and are trapped by the magnetic field, and held in place by their attraction to the anode. Some of the electrons spiral down towards the anode, circulating around the spike in a Hall current. When they reach the anode they impact the uncharged propellant and cause it to be ionized, before finally reaching the anode and closing the circuit.

Field emission electric propulsion

Field emission electric propulsion (FEEP) thrusters use a very simple system of accelerating liquid metal ions to create thrust. Most designs use either caesium or indium as the propellant. The design consists of a small propellant reservoir that stores the liquid metal, a very small slit that the liquid flows through, and then the accelerator ring. Caesium and indium are used due to their high atomic weights, low ionization potentials, and low melting points. Once the liquid metal reaches the inside of the slit in the emitter, an electric field applied between the emitter and the accelerator ring causes the liquid metal to become unstable and ionize. This creates a positive ion, which can then be accelerated in the electric field created by the emitter and the accelerator ring. These positively charged ions are then neutralized by an external source of electrons in order to prevent charging of the spacecraft hull.

Electromagnetic thrusters

Pulsed inductive thrusters (PIT)

Pulsed inductive thrusters (PIT) use pulses of thrust instead of one continuous thrust, and have the ability to run on power levels in the order of Megawatts (MW). PITs consist of a large coil encircling a cone shaped tube that emits the propellant gas as shown in the diagram. Ammonia is the gas commonly used in PIT engines. For each pulse of thrust the PIT gives, a large charge first builds up in a group of capacitors behind the coil and is then released. This creates a current that moves circularly in the direction of jθ. The current then creates a magnetic field in the outward radial direction (Br), which then creates a current in the ammonia gas that has just been released in the opposite direction of the original current. This opposite current ionizes the ammonia and these positively charged ions are accelerated away from the PIT engine due to the electric field jθ crossing with the magnetic field Br, which is due to the Lorentz Force.

Magnetoplasmadynamic (MPD) / lithium Lorentz force accelerator (LiLFA)

Magnetoplasmadynamic (MPD) thrusters and lithium Lorentz force accelerator (LiLFA) thrusters use roughly the same idea with the LiLFA thruster building off of the MPD thruster. Hydrogen, argon, ammonia, and nitrogen gas can be used as propellant. In a certain configuration, the ambient gas in Low Earth Orbit (LEO) can be used as a propellant. The gas first enters the main chamber where it is ionized into plasma by the electric field between the anode and the cathode. This plasma then conducts electricity between the anode and the cathode. This new current creates a magnetic field around the cathode which crosses with the electric field, thereby accelerating the plasma due to the Lorentz Force. The LiLFA thruster uses the same general idea as the MPD thruster, except for two main differences. The first difference is that the LiLFA uses lithium vapor, which has the advantage of being able to be stored as a solid. The other difference is that the cathode is replaced by multiple smaller cathode rods packed into a hollow cathode tube. The cathode in the MPD thruster is easily corroded due to constant contact with the plasma. In the LiLFA thruster the lithium vapor is injected into the hollow cathode and is not ionized to its plasma form/corrode the cathode rods until it exits the tube. The plasma is then accelerated using the same Lorentz Force.

Electrodeless plasma thrusters

Electrodeless plasma thrusters have two unique features: the removal of the anode and cathode electrodes and the ability to throttle the engine. The removal of the electrodes takes away the factor of erosion which limits lifetime on other ion engines. Neutral gas is first ionized by electromagnetic waves and then transferred to another chamber where it is accelerated by an oscillating electric and magnetic field, also known as the ponderomotive force. This separation of the ionization and acceleration stage give the engine the ability to throttle the speed of propellant flow, which then changes the thrust magnitude and specific impulse values.

Electrothermal thrusters

Electrothermal thrusters use electric power to accelerate propellant. There are several types:

1. Resistojet
2. Arcjet
3. Microwave electrothermal thrusters
4. Ion Cyclotron Heating thrusters (VASIMR)

Helicon double layer thruster

A helicon double layer thruster is a type of plasma thruster, which ejects high velocity ionized gas to provide thrust to a spacecraft. In this thruster design, gas is injected into a tubular chamber (the *source tube*) with one open end. Radio frequency AC power (at 13.56 MHz in the prototype design) is coupled into a specially shaped antenna wrapped around the chamber. The electromagnetic wave emitted by the antenna causes the gas to break down and form a plasma. The antenna then excites a Helicon wave in the plasma, which further heats the plasma. The device has a roughly constant magnetic field in the source tube (supplied by Solenoids in the prototype), but the magnetic field diverges and rapidly decreases in magnitude away from the source region, and might be thought of as a kind of magnetic nozzle. In operation, there is a sharp boundary between the high density plasma inside the source region, and the low density plasma in the exhaust, which is associated with a sharp change in electrical potential. The plasma properties change rapidly across this boundary, which is known as a *current free electric double layer*. The electrical potential is much higher inside the source region than in the exhaust, and this serves both to confine most of the electrons, and to accelerate the ions away from the source region. Enough electrons escape the source region to ensure that the plasma in the exhaust is neutral overall.

Comparisons

The following table compares actual test data of some ion thrusters:

Engine	Propellant	Required Power (kW)	Specific Impulse (s)	Thrust (mN)
NSTAR	Xenon	2.3	3,300	92
NEXT	Xenon	7.7	4,300	327
NEXIS	Xenon	20.5	6,000-7,500	400
HiPEP	Xenon	25-50	6,000-9,000	460-670
RIT 22	Xenon	5	3,000-6,000	50 - 200
Hall effect	Bismuth	25	3,000	1,130
Hall effect	Bismuth	140	8,000	2,500
Hall effect	Xenon	25	3,250	950
Hall effect	Xenon	75	2,900	2,900
FEEP	Liquid Caesium	$6x10^{-5}$-0.06	6,000-10,000	0.001-1
VASIMR	Argon	200	3,000-30,000	~5000

The following thrusters are highly experimental and have been tested only in pulse mode.

Engine	Propellant	Required Power (kW)	Specific Impulse (s)	Thrust (mN)
MPDT	Hydrogen	1,500	4,900	26,300
MPDT	Hydrogen	3,750	3,500	88,500
MPDT	Hydrogen	7,500	6,000	60,000
LiLFA	Lithium Vapor	500	4,077	12,000

Lifetime

A major limiting factor of ion thrusters is their small thrust; however, it is generated at a high propellant efficiency (mass utilisation, specific impulse). The efficiency comes from the high exhaust velocity, which in turn demands high energy, and the performance is ultimately limited by the available spacecraft power.

The low thrust requires ion thrusters to provide continuous thrust for a very long time in order to achieve the needed change in velocity (delta-v) for a particular mission. To achieve these delta-vs, ion thrusters are designed to last for periods of weeks to years.

In practice the lifetime of electrostatic ion thrusters is limited by several processes:

- In electrostatic gridded ion thruster design, charge-exchange ions produced by the beam ions with the neutral gas flow can be accelerated towards the negatively biased accelerator grid and cause grid erosion. End-of-life is reached when either a structural failure of the grid occurs or the holes in the accelerator grid become so large that the ion extraction is largely affected (e.g. by the occurrence of electron backstreaming). Grid erosion cannot be avoided and is the major lifetime-limiting factor. By a thorough grid design and material selection, lifetimes of 20,000 hours and far beyond are reached, which is sufficient to fulfill current space missions.

A test of the NASA Solar electric propulsion Technology Application Readiness (NSTAR) electrostatic ion thruster resulted in 30,472 hours (roughly 3.5 years) of continuous thrust at maximum power. The test was concluded prior to any failure and test results showed the engine was not approaching failure either.

- Hall thrusters suffer from very strong erosion of the ceramic discharge chamber. Due to the rather high discharge voltages of up to 1000V energetic ions can impinge to the chamber walls and erode material. Lifetimes of a few thousand hours are reached.

Propellants

Ionization energy represents a very large percentage of the energy needed to run ion drives. The ideal propellant for ion drives is thus a propellant molecule or atom that is easy to ionise, that has a high mass/ionisation energy ratio. In addition, the propellant should not cause erosion of the thruster to any great degree to permit long life; and should not contaminate the vehicle.

Many current designs use xenon gas as it is easy to ionise, has a reasonably high atomic number, its inert nature, and low erosion. However, xenon is globally in short supply and very expensive.

Older designs used mercury, but this is toxic and expensive, tended to contaminate the vehicle with the metal and was difficult to feed accurately.

Other propellants such as bismuth show promise and are areas of research, particularly for gridless designs such as Hall effect thrusters.

VASIMR design (and other plasma based engines) are theoretically able to use practically any material for propellant. However, in current tests the most practical propellant is argon, which is a relatively abundant and cheap gas.

Energy efficiency

Ion thrusters are frequently quoted with an efficiency metric. This efficiency is the kinetic energy of the exhaust jet emitted per second divided by the electrical power into the device.

The actual overall system energy efficiency in use is determined by the propulsive efficiency which in turn depends on vehicle speed as well as the exhaust speed. Some thrusters can vary their exhaust speed in operation, but all can be designed with different exhaust speeds. At the lower end of Isps the overall efficiency drops because the ionisation takes up a larger percentage energy, and at the high end propulsive efficiency is reduced.

Optimal efficiencies and exhaust velocities can thus be calculated for any given mission to give minimum overall cost.

Applications

Ion thrusters have many applications for in-space propulsion. The best applications of the thrusters make use of the long lifetime when significant thrust is not needed. Examples of this include orbit transfers, attitude adjustments, drag compensation for low earth orbits, transporting cargo such as chemical fuels between propellant depots and ultra fine adjustments for more scientific missions. Ion thrusters can also be used for interplanetary and deep space missions where time is not crucial. Continuous thrust over a very long time can build up a larger velocity than traditional chemical rockets.

Missions

Of all the electric thrusters, ion thrusters have been the most seriously considered commercially and academically in the quest for interplanetary missions and orbit raising maneuvers. Ion thrusters are seen as the best solution for these missions as they require very high change in velocity overall that can be built up over long periods of time.

Operational missions

Several spacecraft have operated with this technology.

SERT

Ion propulsion systems were first demonstrated in space by the NASA Lewis (now Glenn Research Center) missions "Space Electric Rocket Test" (SERT) I and II. The first was SERT-1, launched July 20, 1964, successfully proved that the technology operated as predicted in space. These were electrostatic ion thrusters using mercury and cesium as the reaction mass The second test, SERT-II, launched on February 3, 1970, verified the operation of two mercury ion engines for thousands of running hours.

Deep Space 1

NASA has developed an ion thruster called NSTAR for use in their interplanetary science missions beginning in the late-1990s. This xenon-propelled ion thruster was first space-tested in the highly successful space probe Deep Space 1, launched in 1998. This was the first use of electric propulsion as the interplanetary propulsion system on a science mission. Based on this NASA-developed technology, the contractor, Hughes, developed the XIPS (Xenon Ion Propulsion System) for performing stationkeeping on geosynchronous satellites.

Artemis

On 12 July 2001, the European Space Agency failed to launch their Artemis telecommunication satellite to desired altitude, and left it in a decaying orbit. The satellite's chemical propellant supply was sufficient to transfer it to a semi-stable orbit, and over the next 18 months the experimental onboard ion propulsion system RIT-10 (intended only for secondary stationkeeping and maneuvering) was utilized to transfer it to a geostationary orbit.

Hayabusa

The Japanese space agency's Hayabusa, which was launched in 2003 and successfully rendezvoused with the asteroid 25143 Itokawa and remained in close proximity for many months to collect samples and information, was powered by four xenon ion engines. It used xenon ions generated by microwave electron cyclotron resonance, and a carbon / carbon-composite material (which is resistant to erosion) for its acceleration grid. Although the ion engines on Hayabusa had some technical difficulties, in-flight reconfiguration allowed one of the four engines to be repaired, and allowed the mission to successfully return to Earth.

Smart 1

The Hall effect thruster is a type of ion thruster that has been used for decades for station keeping by the Soviet Union and is now also applied in the West: the European Space Agency's satellite Smart 1, launched in 2003, used it (Snecma PPS-1350-G). This satellite completed its mission on 3 September 2006, in a controlled collision on the Moon's surface, after a trajectory deviation to be able to see the 3 meter crater the impact created on the visible side of the moon.

Dawn

Dawn was launched on 27 September 2007 to explore the asteroid Vesta and the dwarf planet Ceres. To cruise from Earth to its targets it uses three Deep Space 1 heritage xenon ion thrusters (firing only one at a time) to take it in a long outward spiral. An extended mission in which Dawn explores other asteroids after Ceres is also possible. Dawn's ion drive is capable of accelerating from 0 to 60 mph (97 km/h) in 4 days.

GOCE

ESA's Gravity Field and Steady-State Ocean Circulation Explorer was launched on March 16, 2009. It will continue to use ion propulsion throughout its twenty month mission to combat the air-drag it experiences in its low orbit.

Planned missions

In addition, several missions are planned to use ion thrusters in the next few years.

GSAT-4

Indian Space Research Organisation will utilize ion thrusters in its GSAT-4 satellite. This will increase the life of satellite from the present 10 years to 15 years.

LISA Pathfinder

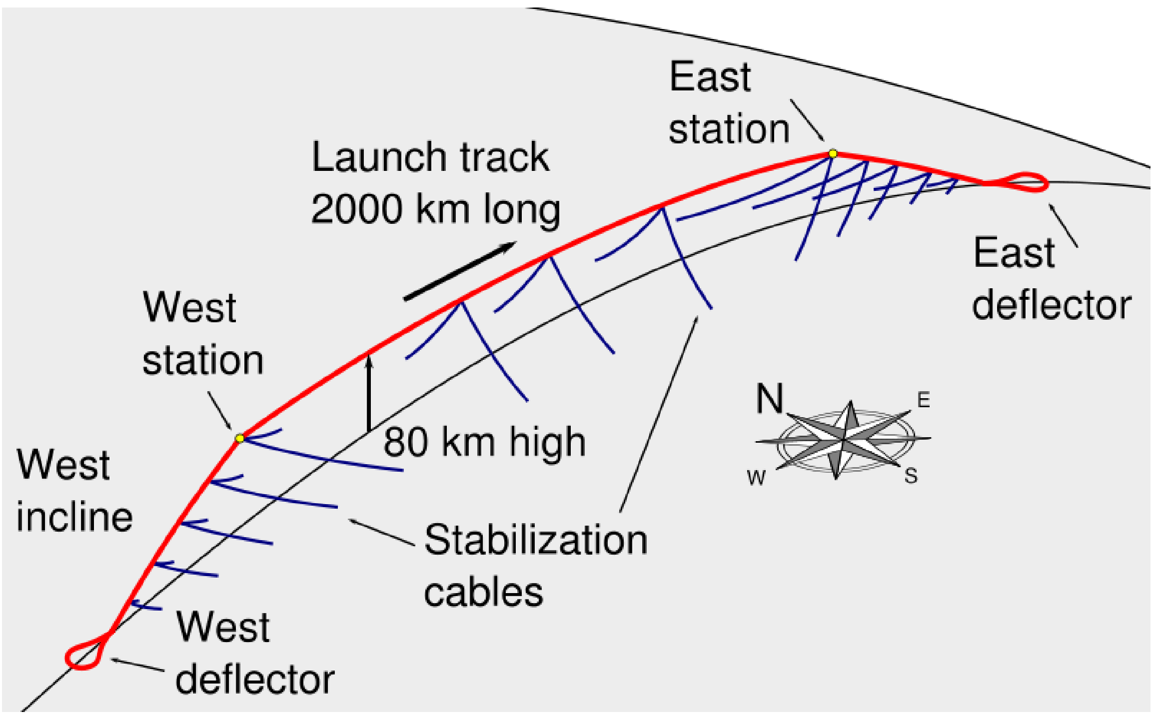
LISA Pathfinder is an ESA spacecraft to be launched in 2011. It will not use ion thrusters as its primary propulsion system, but will use both colloid thrusters and FEEP for very precise altitude control—the low thrusts of these propulsion devices make it possible to move the spacecraft incremental distances very accurately. It is a test for the possible LISA mission.

International Space Station

As of February 2010, a 2011/2012 launch of an Ad Astra VF-200 200 kW VASIMR electromagnetic thruster is planned for placement and testing on the International Space Station. The VF-200 is a flight version of the VX-200. though it may be later. Since the available power from the ISS is less than 200 kW, the ISS VASIMR will include a trickle-charged battery system allowing for 15 min pulses of thrust. Testing of the engine on ISS is valuable because ISS orbits at a relatively low altitude and experiences fairly high levels of atmospheric drag, making periodic boosts of altitude necessary. Currently, altitude reboosting by chemical rockets fulfills this requirement. If the tests of VASIMR reboosting of the ISS goes according to plan, the increase in specific impulse could mean that the cost of fuel for altitude reboosting will be one-twentieth of the current $210 million annual cost. Hydrogen is generated by the ISS as a by-product, which is currently vented into space.

Chapter 8

Launch Loop



Launch loop. The red marked line is the moving loop itself, blue lines are stationary cables.

A **launch loop** or **Lofstrom loop** is a published design for an active structure maglev cable transport system intended for orbital launch that would be around 2,000 km (1,240 mi) long and maintained at an altitude of up to 80 km (50 mi). A launch loop would be held up at this altitude by momentum of the belt as it circulates around the structure. This circulation, in effect, transfers the weight of the structure onto a pair of magnetic bearings, one at each end, which support it.

Launch loops are intended to achieve non-rocket spacelaunch of vehicles weighing 5 metric tons by electromagnetically accelerating them so that they are projected into Earth orbit or even beyond. This would be achieved by the flat part of the cable which forms an acceleration track above the atmosphere.

The published cost estimates for a working launch loop are significantly lower than a space elevator and additionally the proposed system has a greater launch capacity, lower payload costs and similar or greater payload masses. Unlike the space elevator, no new materials need to be developed.

The system is designed to be suitable for launching humans for space tourism, space exploration and space colonization, and provides a relatively low 3*g* acceleration.

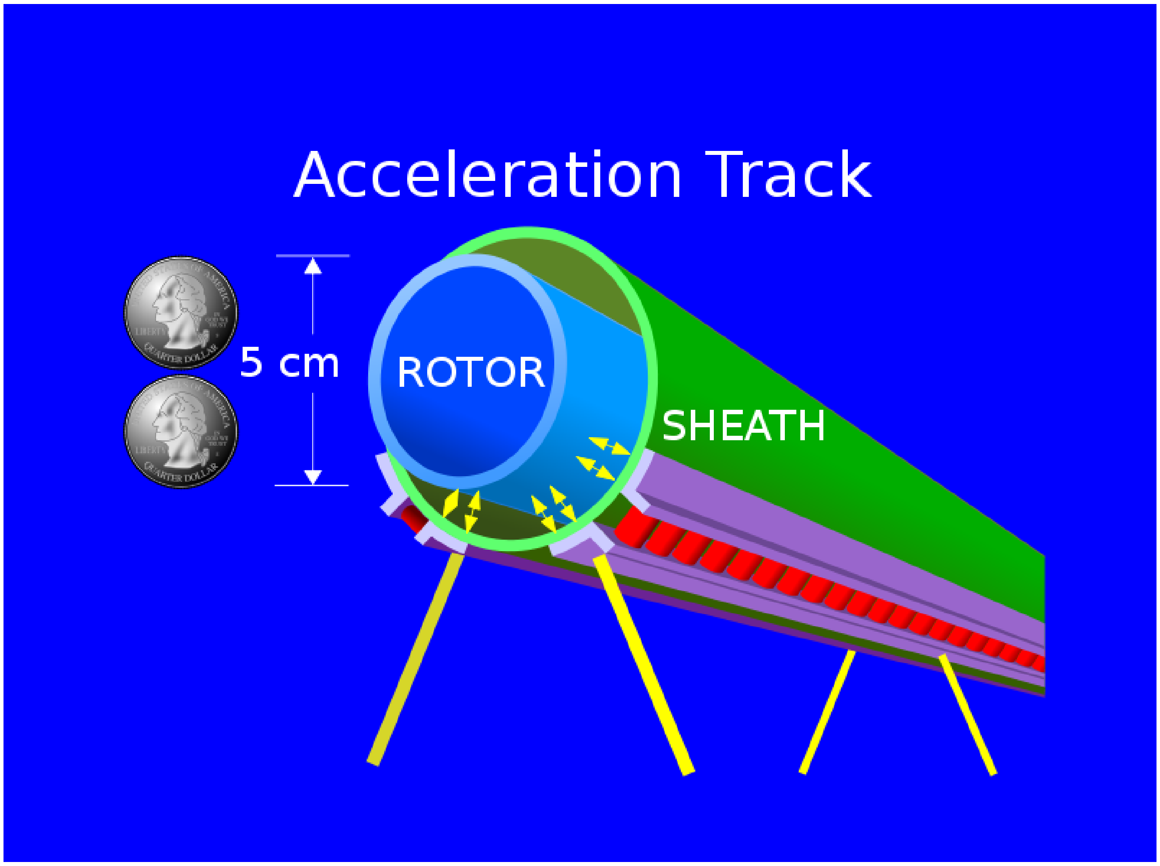
History

Launch loops were described by Keith Lofstrom in November 1981 Reader's Forum of the American Astronautical Society News Letter, and in the August 1982 L5 News.

In 1982 Paul Birch published a series of papers in *Journal of the British Interplanetary Society* which described orbital rings and described a form which he called Partial Orbital Ring System (PORS).

The launch loop idea was worked on in more detail around 1983–1985 by Lofstrom. It is a fleshed-out version of PORS specifically arranged to form a mag-lev acceleration track suitable for launching humans into space; but whereas the orbital ring used superconducting magnetic levitation, launch loops use Electromagnetic suspension (EMS).

Description



Launch loop accelerator section (return cable not shown)

A launch loop is proposed to be a structure around 2,000 km long and 80 km high. The loop runs along at 80 km above the earth for 2000 km then descends to earth before looping back on itself rising back to 80 km above the earth to follow the reverse path then looping back to the starting point. The loop would be in the form of a tube, known as the *sheath*. Floating within the sheath is another continuous tube, known as the *rotor* which is a sort of belt or chain. The rotor is an iron tube approximately 5 cm (2 inches) in diameter, moving around the loop at 14 km/s (31 000 miles per hour).

Although the overall loop is very long, at around 4,000 km circumference, the rotor itself would be thin, around 5 cm diameter and the sheath is not much bigger.

Ability to stay aloft

When at rest, the loop is at ground level. The rotor is then accelerated up to speed. As the rotor speed increases, it curves to form an arc. The sheath forces it to follow a curve steeper than the rotor's natural ballistic curve, which, in turn, exerts a reactive centrifugal force on the sheath, holding it aloft. The loop would be anchored to the ground to remain at a fixed height.

Once raised, the structure requires continuous power to overcome the energy dissipated. Additional energy would be needed to power any vehicles that are launched.

Launching payloads

To launch, vehicles are raised up on an 'elevator' cable that hangs down from the West station loading dock at 80 km, and placed on the track. The payload applies a magnetic field which generates eddy currents in the fast-moving rotor. This both lifts the payload away from the cable, as well as pulls the payload along with 3*g* (30 m/s^2) acceleration. The payload then rides the rotor until it reaches the required orbital velocity, and leaves the track.

If a stable or circular orbit is needed, once the payload reaches the highest part of its trajectory then an on-board rocket engine ("kick motor") or other means is needed to circularize the trajectory to the appropriate Earth orbit.

The eddy current technique is compact, lightweight and powerful, but inefficient. With each launch the rotor temperature increases by 80 kelvins due to power dissipation. If launches are spaced too close together, the rotor temperature can approach 770 °C (1043 K), at which point the iron rotor loses its ferromagnetic properties and rotor containment is lost.

Capacity and capabilities

Closed orbits with a perigee of 80 km quite quickly decay and re-enter, but in addition to such orbits, a launch loop by itself would also be capable of directly injecting payloads into escape orbits, gravity assist trajectories past the Moon, and other non closed orbits such as close to the Trojan points.

To access circular orbits using a launch loop a relatively small 'kick motor' would need to be launched with the payload which would fire at apogee and would circularise the orbit. For GEO insertion this would need to provide a delta-v of about 1.6 km/s, for LEO to circularise at 500 km would require a delta-v of just 120 m/s. Conventional rockets require delta-vs of roughly 10 and 14 km/s to reach LEO and GEO respectively.

Launch loops in Lofstrom's design are placed close to the equator and can only directly access equatorial orbits. However other orbital planes might be reached via high altitude plane changes, lunar perturbations or aerodynamic techniques.

Launch rate capacity of a launch loop is ultimately limited by the temperature and cooling rate of the rotor to 80 per hour, but that would require a 17 GW power station; a more modest 500 MW power station is sufficient for 35 launches per day.

Economics

For a launch loop to be economically viable it would require customers with sufficiently large payload launch requirements.

Lofstrom estimates that an initial loop costing roughly $10 billion with a one-year payback could launch 40,000 metric tons per year, and cut launch costs to $300/kg, or for $30 billion, with a larger power generation capacity, the loop would be capable of launching 6 million metric tons per year, and given a five-year payback period, the costs for accessing space with a launch loop could be as low as $3/kg.

Comparisons

Advantages of launch loops

Lofstrom's launch loops are expected to launch at high rates (many launches per hour, independent of weather), and are not inherently polluting. Rockets create pollution such as nitrates in their exhausts due to high exhaust temperature, and can create greenhouse gases depending on propellant choices. Launch loops as a form of electric propulsion can be clean, and can be run on geothermal, nuclear, wind, solar or any other power source, even intermittent ones, as the system has huge built-in power storage capacity.

Unlike space elevators which would have to travel through the Van Allen belts over several days, launch loop passengers can be launched to low earth orbit, which is below the belts, or through them in a few hours. This would be a similar situation to that faced by the Apollo astronauts, who had radiation doses 200 times lower than the space elevator would give.

Unlike space elevators which are subjected to the risks of space debris and meteorites along their whole length, launch loops are to be situated at an altitude where orbits are unstable due to air drag. Since debris does not persist, it only has one chance to impact the structure. Whereas the collapse period of space elevators is expected to be of the order of years, damage or collapse of loops in this way is expected to be rare. In addition, launch loops themselves are not a significant source of space debris, even in an accident. All debris generated has a perigee that intersects the atmosphere or is at escape velocity.

Launch loops are intended for human transportation, to give a safe 3*g* acceleration which the vast majority of people would be capable of tolerating well, and would be a much faster way of reaching space than space elevators.

Launch loops would be quiet in operation, and would not cause any sound pollution, unlike rockets.

Finally, their low payload costs are compatible with large-scale commercial space tourism and even space colonisation.

Difficulties of launch loops

A running loop would have an extremely large amount of energy in the form of linear momentum. While the magnetic suspension system would be highly redundant, with failures of small sections having essentially no effect at all, if a major failure did occur the energy in the loop (1.5×10^{15} joules or 1.5 petajoules) would be approaching the same total *energy* release as a nuclear bomb explosion (350 kilotons of TNT equivalent), although not emitting nuclear radiation.

While this is a large amount of energy, it is unlikely that this would destroy very much of the structure due to its very large size, and because most of the energy would be deliberately dumped at preselected places when the failure is detected. Steps might need to be taken to lower the cable down from 80 km altitude with minimal damage, such as parachutes.

Therefore for safety and astrodynamic reasons, launch loops are intended to be installed over an ocean near the equator, well away from habitation.

The published design of a launch loop requires electronic control of the magnetic levitation to minimise power dissipation and to stabilise the otherwise under-damped cable.

The instabilities are primarily in the turnaround sections as well as the cable.

The turnaround sections are potentially unstable, since movement of the rotor away from the magnets gives reduced magnetic attraction, whereas movements closer gives increased attraction. In either case instability occurs. This problem is routinely solved with existing servocontrol systems that vary the strength of the magnets. Although servo reliability is a potential issue, at the high speed of the rotor, very many consecutive sections would need to fail for the rotor containment to be lost.

The cable sections also share this potential issue, although the forces are much lower. However, an additional instability is present in that the cable/sheath/rotor may undergo meandering modes (similar to a Lariat chain) that grow in amplitude without limit. Lofstrom believes that this instability also can be controlled in real time by servomechanisms, although this has never been attempted.

Competing and similar designs

In works by Alexander Bolonkin it is suggested that Lofstrom's project has many non-solved problems and that it is very far from a current technology. For example, the Lofstrom project has expansion joints between 1.5 meter iron plates. Their speeds (under gravitation, friction) can be different and Bolonkin claims that they could wedge in the tube; and the force and friction in the ground 28 km diameter turnaround sections are gigantic. In 2008 Bolonkin proposed a simple rotated close-loop cable to launch the space apparatus in a way suitable for current technology.

Another project, the **space cable**, is a smaller design by John Knapman that is intended for launch assist for conventional rockets, and suborbital tourism. The space cable design uses electrodynamic levitation rather than electromagnetic levitation and discrete 'bolt's rather than a continuous rotor as with the launch loop architecture. John Knapman has also mathematically shown that the meander instability can be tamed.

Chapter 9

Magnetic Sail

A **magnetic sail** or **magsail** is a proposed method of spacecraft propulsion which would use a static magnetic field to deflect charged particles radiated by the Sun as a plasma wind, and thus impart momentum to accelerate the spacecraft. A magnetic sail could also thrust directly against planetary and solar magnetospheres.

Principles of operation and design

The solar wind is a tenuous stream of plasma that flows outwards from the Sun: near the Earth's orbit, it contains several million protons and electrons per cubic meter and flows at 400 to 600 kilometres per second (250 to 370 mi/s). The magnetic sail introduces a magnetic field into this plasma flow, perpendicular to the motion of the charged particles, which can deflect the particles from their original trajectory: the momentum of the particles is then transferred to the sail, leading to a thrust on the sail. One advantage of magnetic or solar sails over (chemical or ion) reaction thrusters is that no reaction mass is depleted or carried in the craft.

In typical magnetic sail designs, the magnetic field is generated by a loop of superconducting wire. Because loops of current-carrying conductors tend to be forced outwards towards a circular shape by their own magnetic field, the sail could be deployed simply by unspooling the conductor and applying a current through it.

For a sail in the solar wind at 1 AU away from the Sun, the field strength required to resist the dynamic pressure of the solar wind is 50 nT (Template:Convert/nT). Zubrin's proposed magnetic sail design would create a bubble of space of 100 km in diameter (62 mi) where solar-wind ions are substantially deflected using a hoop 50 km (31 mi) in radius. The minimum weight of such a coil is constrained by material strength limitations at roughly 40 tonnes and it would generate 70 newtons (16 lb_f) of thrust, giving a mass/thrust ratio of 600 kg/N. It is not clear how such a coil would be cooled.

The operation of magnetic sails using plasma wind is analogous to the operation of solar sails using the radiation pressure of photons emitted by the Sun. Although solar wind particles have rest mass and photons do not, sunlight has thousands of times more momentum than the solar wind. Therefore, a magnetic sail must deflect a proportionally larger area of the solar wind than a comparable solar sail to generate the same amount of thrust. However, it need not be as massive as a solar sail because the solar wind is deflected by a magnetic field instead of a large physical sail. Conventional materials for solar sails weigh around 7 grams per square metre (0.0014 lb/sq ft), giving a thrust of 1e-5 N/m^2 at 1 AU. This gives a mass/thrust ratio of at least 700 kg/N, similar to a magnetic sail, neglecting other structural components.

The solar and magnetic sails have a thrust that falls off as the square of the distance from the Sun.

When close to a planet with a strong magnetosphere, e.g. Earth or a gas giant, the magsail could generate more thrust by interacting with the magnetosphere instead of the solar wind, and may therefore be more efficient.

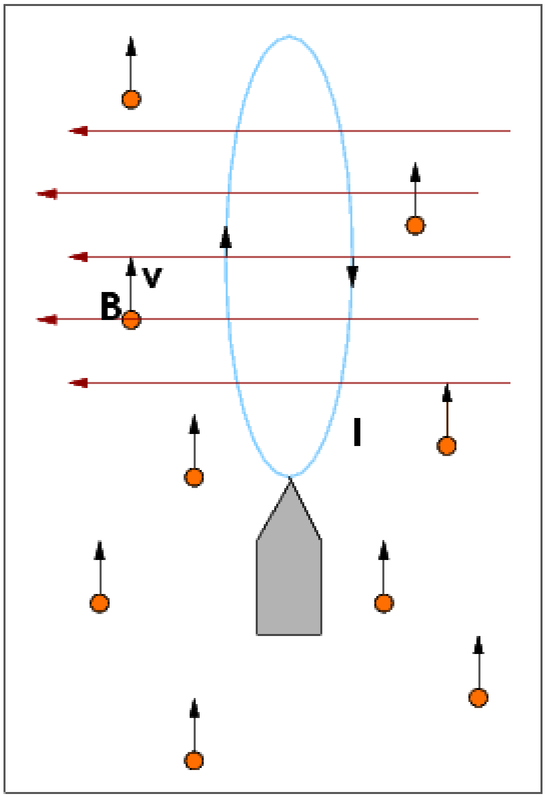
Mini-magnetospheric plasma propulsion

In order to reduce the size and weight of the magnet of the magnetic sail, it may be possible to *inflate* the magnetic field using a plasma in the same way that the plasma around the earth stretches out the Earth's magnetic field in the magnetosphere. In this approach, called **mini-magnetospheric plasma propulsion** (M2P2), currents running through the plasma augment and partially replace the currents in the coil. This is expected to be especially useful far from the Sun, where the increased effective size of a M2P2 sail compensates for the reduced dynamic pressure of the solar wind. The original NASA design proposes a spacecraft containing a can-shaped electromagnet into which a plasma is injected. The plasma pressure stretches the magnetic field and inflates a bubble of plasma around the spacecraft. The current in the plasma in this case augments and partially replaces currents in the coils. The plasma then generates a kind of miniaturized magnetosphere around the spacecraft, analogous to the magnetosphere that surrounds the earth. The protons and electrons which make up the solar wind are deflected by this magnetosphere and the reaction accelerates the spacecraft. The thrust of the M2P2 device would be steerable to some extent, potentially allowing the spacecraft to 'tack' into the solar wind and allowing efficient changes of orbit.

In the case of the (M2P2) system the spacecraft releases gas to create the plasma needed to maintain the somewhat leaky plasma bubble. The M2P2 system therefore has an effective *specific impulse* which is the amount of gas consumed per newton of thrust. This is a figure of merit usually used for rockets, where the fuel is actually reaction mass. Robert Winglee, who originally proposed the M2P2 technique, calculates a *specific impulse* of 200 kN·s/kg (roughly 50 times better than the space shuttle main engine). These calculations suggest that the system requires on the order of a kilowatt of power per newton of thrust, considerably lower than electric thrusters, and that the system generates the same thrust anywhere within the heliopause because the sail spreads automatically as the solar wind becomes less dense. However, this technique is less well understood than the simpler magnetic sail and issues of how large and heavy the magnetic coil would have to be or whether the momentum from the solar wind can be efficiently transferred to the spacecraft are under dispute.

The expansion of the magnetic field using plasma injected has been successfully tested in a large vacuum chamber on Earth, but the development of thrust was not part of the experiment. A beam-powered variant, MagBeam, is also under development.

Modes of operation



A magnetic sail in a wind of charged particles. The sail generates a magnetic field, represented by red arrows, which deflects the particles into the page. The force on the sail is out of the page.

In a plasma wind

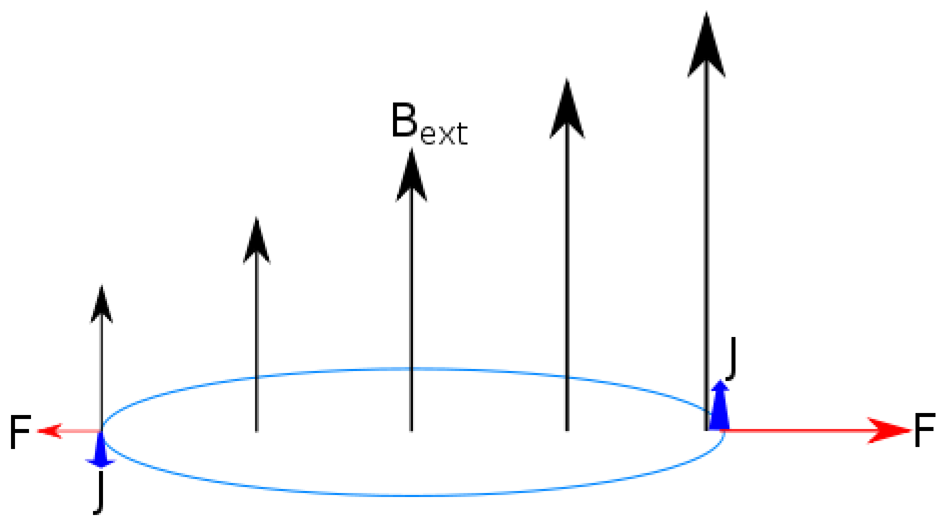
When operating away from planetary magnetospheres, a magnetic sail would force the positively charged protons of the solar wind to curve as they passed through the magnetic field. The change of momentum of the protons would thrust against the magnetic field, and thus against the field coil.

Just as with solar sails, magnetic sails can "tack." If a magnetic sail orients at an angle relative to the solar wind, charged particles are deflected preferentially to one side and the magnetic sail is pushed laterally. This means that magnetic sails could maneuver to most orbits.

In this mode, the amount of thrust generated by a magnetic sail falls off with the square of its distance from the Sun as the flux density of charged particles reduces. Solar weather also has major effects on the sail. It is possible that the plasma eruption from a severe solar flare could damage an efficient, fragile sail.

A common misconception is that a magnetic sail cannot exceed the speed of the plasma pushing it. As the speed of a magnetic sail increases, its acceleration becomes more dependent on its ability to tack efficiently. At high speeds, the plasma wind's direction will seem to come increasingly from the front of the spacecraft. Advanced sailing spacecraft might deploy field coils as "keels," so the spacecraft could use the difference in vector between the solar magnetic field and the solar wind, much as sailing yachts do.

Inside a planetary magnetosphere



A magnetic sail in a spatially-varying magnetic field. Because the vertical external field B_{ext} is stronger on one side than the other, the leftward force on the left side of the ring is smaller than the rightward force on the right side of the ring, and the net force on the sail is to the right.

Inside a planetary magnetosphere, a magnetic sail can thrust against a planet's magnetic field, especially in an orbit that passes over the planet's magnetic poles, in a similar manner to an electrodynamic tether.

The range of maneuvers available to a magnetic sail inside a planetary magnetosphere are more limited than in a plasma wind. Just as with the more familiar small-scale magnets used on Earth, a magnetic sail can only be attracted towards the magnetosphere's poles or repelled from them, depending on its orientation.

When the magnetic sail's field is oriented in the opposite direction to the magnetosphere it experiences a force inward and toward the nearest pole, and when it is oriented in the same direction as the magnetosphere it experiences the opposite effect. A magnetic sail oriented in the same direction as the magnetosphere is not stable, and will have to prevent itself from being flipped over to the opposite orientation by some other means.

The thrust that a magnetic sail delivers within a magnetosphere decreases with the fourth power of its distance from the planet's internal magnetic dynamo.

This limited maneuvering capability is still quite useful. By varying the magnetic sail's field strength over the course of its orbit, a magnetic sail can give itself a "perigee kick" raising the altitude of its orbit's apogee.

Repeating this process with each orbit can drive the magnetic sail's apogee higher and higher, until the magnetic sail is able to leave the planetary magnetosphere and catch the solar wind. The same process in reverse can be used to lower or circularize the apogee of a magsail's orbit when it arrives at a destination planet.

In theory, it is possible for a magnetic sail to launch directly from the surface of a planet near one of its magnetic poles, repelling itself from the planet's magnetic field. However, this requires the magnetic sail to be maintained in its "unstable" orientation. A launch from Earth requires superconductors with 80 times the current density of the best known high-temperature superconductors.

Interstellar travel

Interstellar space contains very small amounts of hydrogen. A fast-moving sail would ionize this hydrogen by accelerating the electrons in one direction and the oppositely-charged protons in the other direction. The energy for the ionization and cyclotron radiation would come from the spacecraft's kinetic energy, slowing the spacecraft. The cyclotron radiation from the acceleration of particles would be an easily detected howl in radio frequencies.

Thus, in interstellar spaceflight outside the heliopause of a star a magnetic sail could act as a parachute to decelerate a spacecraft. This removes any fuel requirements for the deceleration half of an interstellar journey, which would benefit interstellar travel enormously. The magsail was first proposed for this purpose in 1985 by Robert Zubrin and Dana Andrews, predating other uses, and evolved from a concept of the Bussard ramjet which used a magnetic scoop to collect interstellar material.

Magnetic sails could also be used with beam-powered propulsion by using a high-power particle accelerator to fire a beam of charged particles at the spacecraft. The magsail would deflect this beam, transferring momentum to the vehicle. This would provide much higher acceleration than a solar sail driven by a laser, but a charged particle beam would disperse in a shorter distance than a laser due to the electrostatic repulsion of its component particles. This dispersion problem could potentially be resolved by accelerating a stream of sails which then in turn transfer their momentum to a magsail vehicle, as proposed by Jordin Kare.

Fictional uses

The magnetic sail first appeared in science-fiction in Poul Anderson's 1967 short story *To Outlive Eternity*, which was followed by the novel *Tau Zero* in 1970. It also features prominently in the science-fiction novels of Michael Flynn, particularly in *The Wreck of the River of Stars* (2003); this book is the tale of the last flight of a magnetic sail ship when fusion rockets based on the Farnsworth-Hirsch Fusor have become the preferred technology.

Chapter 10

Magnetohydrodynamic Drive and Magnetoplasmadynamic Thruster

Magnetohydrodynamic drive

The *Yamato 1* on display in Kobe, Japan. The first known working prototype.

The front of the *Yamato 1*

A MHD thruster from the boat, at the Ship Science Museum in Tokyo.

A **magnetohydrodynamic drive** or **MHD propulsor** is a method for propelling seagoing vessels using only electric and magnetic fields with no moving parts, using magnetohydrodynamics. The working principle involves electrification of the propellant (gas or water) which can then be directed by a magnetic field, pushing the vehicle in the opposite direction. Although some working prototypes exist, MHD drives remain impractical and exist mostly in the world of science fiction.

Principle

Ship propulsion

An electric current is passed through seawater in the presence of an intense magnetic field, which interacts with the magnetic field of the current through the water. Functionally, the seawater is then the moving, conductive part of an electric motor. Pushing the water out the back accelerates the vehicle in the forward direction.

MHD is attractive because it has no moving parts, which means that a good design might be silent, reliable, efficient, and inexpensive.

The major problem with MHD is that with current technologies it is more expensive and much slower than a propeller driven by an engine. The extra expense is from the large generator that must be driven by an engine. Such a large generator is not required when an engine directly drives a propeller.

Spacecraft propulsion

A number of experimental methods of spacecraft propulsion are based on magnetohydrodynamic principles. In these the working fluid is usually a plasma or a thin cloud of ions. Some of the techniques include various kinds of ion thruster, the magnetoplasmadynamic thruster, and the variable specific impulse magnetoplasma rocket.

Prototypes

The first prototype of this kind of propulsion was built and tested in 1965 by Steward Way, a professor of mechanical engineering at the University of California, Santa Barbara. Way, on leave from his job at Westinghouse Electric, assigned his senior year undergraduate students to develop a submarine with this new propulsion system. In 1991, another prototype, the *Yamato 1*, was completed in Japan by the Ship & Ocean Foundation (later known as the Ocean Policy Research Foundation). The ship was first successfully propelled in Kobe harbour in June 1992. Yamato 1 is propelled by two MHD thrusters that run without any moving parts.

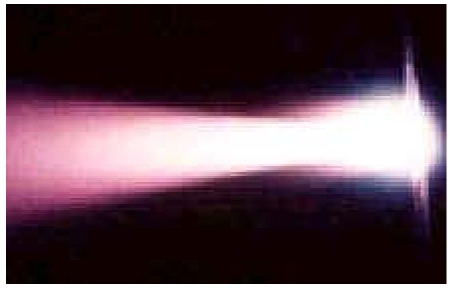
Fiction

In the *Star Trek* universe, the sub-light impulse engines are MHDs according to the *Star Trek: The Next Generation Technical Manual*, where the working fluid/propellant is the plasma generated by nuclear fusion reactors.

The "Oregon", a ship in the Oregon Files series of books by author Clive Cussler, has a magnetohydrodynamic drive.

The film adaptation of *The Hunt for Red October* popularized the magnetohydrodynamic drive as a "caterpillar drive" for submarines, an undetectable "silent drive" intended to achieve stealth in submarine warfare. In reality, the current traveling through the water would create gases and noise, and the magnetic fields would induce a detectable magnetic signature. In the novel, of which the movie was an adaptation, the caterpillar was a pumpjet.

Magnetoplasmadynamic thruster



An MPD thruster during test firing

The **Magnetoplasmadynamic (MPD) thruster** (MPDT) is a form of electrically powered spacecraft propulsion which uses the Lorentz force (a force resulting from the interaction between a magnetic field and an electric current) to generate thrust. It is sometimes referred to as Lorentz Force Accelerator (LFA) or (mostly in Japan) MPD arcjet.

Generally, a gaseous fuel is ionized and fed into an acceleration chamber, where the magnetic and electrical fields are created using a power source. The particles are then propelled by the Lorentz force resulting from the interaction between the current flowing through the plasma and the magnetic field (which is either externally applied, or induced by the current) out through the exhaust chamber. Unlike chemical propulsion, there is no combustion of fuel. As with other electric propulsion variations, both specific impulse and thrust increase with power input, while thrust per watt drops.

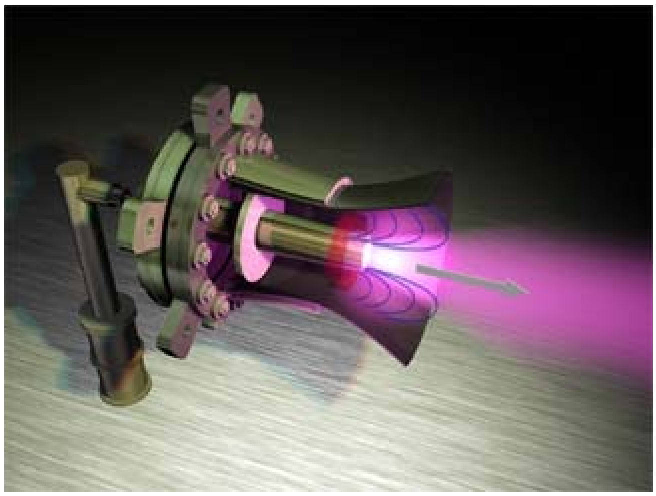
There are two main types of MPD thrusters, applied-field and self-field. Applied-field thrusters have magnetic rings surrounding the exhaust chamber to produce the magnetic field, while self-field thrusters have a cathode extending through the middle of the chamber. Applied fields are necessary at lower power levels, where self-field configurations are too weak. Various propellants such as xenon, neon, argon, hydrazine, and lithium have been used, with lithium generally being the best performer.

The VASIMR is a totally different type of engine that attempts to provide the same level of performance as MPD but operates on a totally different principles : it is an electrothermal device, where the energy is first applied to the propellant in order to increase its random kinetic energy (temperature), in case of VASIMR the propellant is heated using RF and then a part of the thermal energy content of the propellant is converted into directed kinetic energy by using an appropriate nozzle, in this case a magnetic nozzle. Details on this engine can be found in the main Variable Specific Impulse Magnetoplasma Rocket article.

Advantages

In theory, MPD thrusters could produce extremely high specific impulses (I_{sp}) with an exhaust velocity of up to and beyond 110,000 m/s, triple the value of current xenon-based ion thrusters, and about 20 times better than liquid rockets. MPD technology also has the potential for thrust levels of up to 200 newtons (N) (45 lbf), by far the highest for any form of electric propulsion, and nearly as high as many interplanetary chemical rockets. This would allow use of electric propulsion on missions which require quick delta-v maneuvers (such as capturing into orbit around another planet), but with many times greater fuel efficiency.

Problems with MPDT



CGI rendering of Princeton University's Lithium-fed Self-Field MPD Thruster (From Popular Mechanics magazine)

MPD thruster technology has been explored academically, but commercial interest has been low due to several remaining problems. One big problem is that power requirements on the order of hundreds of kilowatts are required for optimum performance. Current interplanetary spacecraft power systems (such as radioisotope thermoelectric generators (RTGs)) and solar arrays are incapable of producing that much power. NASA's Project Prometheus reactor was expected to generate power in the hundreds of kilowatts range but was discontinued in 2005.

A project to produce a space-going nuclear reactor designed to generate 600 kilowatts of electrical power began in 1963 and ran for most of the 1960s in the USSR. It was to power a communication satellite which was in the end not approved. Nuclear reactors supplying kilowatts of electrical power (of the order of ten times more than current RTG power supplies) have been orbited by the USSR: RORSAT; and TOPAZ.

Plans to develop a megawatt-scale nuclear reactor for the use aboard a manned spaceship were announced in 2009 by Russian nuclear Kurchatov Institute, national space agency Roskosmos, and confirmed by the President of Russia in November 2009 address.

Another plan, proposed by Bradley C. Edwards, is to beam power from the ground. This plan utilizes 5 200 kW Free electron lasers at 0.84 micrometres with adaptive optics on the ground to beam power to the MPD-powered spacecraft, where it is converted to electricity by GaAs photovoltaic panels. The tuning of the laser wavelength of 0.840 micrometres (1.48 eV per photon) and the PV panel bandgap of 1.43 eV to each other produces an estimated conversion efficiency of 59% and a predicted power density of up to 540 kW/m^2. This would be sufficient to power a MPD upper stage, perhaps to lift satellites from LEO to GEO.

Other problem with MPD technology has been the degradation of cathodes due to evaporation driven by high current densities (in excess of 100 amps/cm^2). The use of lithium and barium propellant mixtures and multi-channel hollow cathodes has been shown in the laboratory to be a promising solution for the cathode erosion problem.

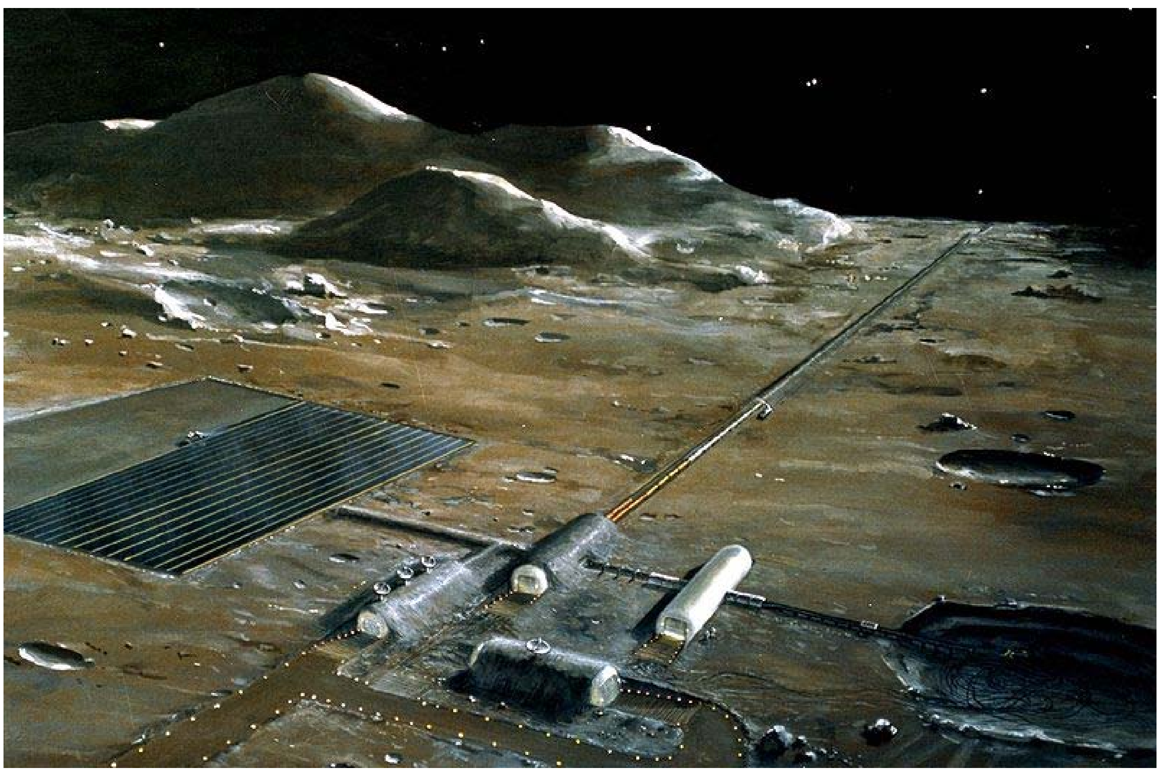
Research

Research on MPD thrusters has been carried out in the US, the former Soviet Union, Japan, Germany, and Italy. Experimental prototypes were first flown on Soviet spacecraft and, most recently, in 1996, on the Japanese Space Flyer Unit, which demonstrated the successful operation of a quasi-steady pulsed MPD thruster in space. Research at Moscow Aviation Institute, RKK Energiya, National Aerospace University, Kharkiv Aviation Institute University of Stuttgart, ISAS, Centrospazio, Alta S.p.A., Osaka University, University of Southern California, Princeton University's Electric Propulsion and Plasma Dynamics Lab (EEPDyL) (where MPD thruster research has continued uninterrupted since 1967), and NASA centers (Jet Propulsion Laboratory and Glenn Research Center), has resolved many problems related to the performance, stability and lifetime of MPD thrusters.

An MPD thruster was tested on board the Japanese Space Flyer Unit as part of EPEX (Electric Propulsion EXperiment) that was launched March 18, 1995 and retrieved by space shuttle mission STS-72 January 20, 1996. To date, it is the only operational MPD thruster to have flown in space as a propulsion system.

Chapter 11

Mass Driver



Artists conception of a mass driver for lunar launch

A **mass driver** or **electromagnetic catapult** is a proposed method of non-rocket spacelaunch which would use a linear motor to accelerate and catapult payloads up to high speeds. All existing and contemplated mass drivers use coils of wire energized by electricity to make electromagnets. Sequential firing of a row of electromagnets accelerates the payload along a path. After leaving the path, the payload continues to move due to momentum.

A mass driver is essentially a coilgun that magnetically accelerates a package consisting of a magnetisable holder containing a payload. Once the payload has been accelerated, the two separate, and the holder is slowed and recycled for another payload.

Mass drivers can be used to propel spacecraft in two different ways: A large, ground-based mass driver could be used to launch spacecraft away from the Earth or another planet. A spacecraft could have a mass driver on board, flinging large pieces of material into space to propel itself. A hybrid design is also possible.

Miniaturized mass drivers can also be used as weapons in a similar manner as classic firearms or cannon using chemical combustion.

Fixed mass drivers

Generally speaking, mass drivers are practical for small objects at a few kilometers per second; for example 1 kg at 2.5 km/s. Heavier objects go proportionally more slowly; and lighter objects may be projected at 20 km/s or more. The limits are generally the cost of the silicon to switch the current and the cost of the power supply and temporary energy storage for it. However, energy can be stored inductively in superconducting coils. A 1 km long mass driver made of superconducting coils can accelerate a 20 kg vehicle to 10.5 km/s at a conversion efficiency of 80%, and average acceleration of 5,600 g. Even so, Earth-based Mass drivers for propelling one-tonne vehicles to orbit are unlikely to be cost effective in the near future.

The Earth's strong gravity and thick atmosphere make such an installation difficult, so many proposals have been put forward to install mass drivers on the moon where the lower gravity and lack of atmosphere significantly reduce the required velocity to reach lunar orbit.

Most serious mass driver designs use superconducting coils to achieve reasonable energetic efficiency (approximately 50%). The best known performance occurs with an aluminum coil as the payload. The coils of the mass-driver induce eddy-currents in the payload's coil, and then act on the resulting magnetic field. There are two sections of a mass-driver. The maximum acceleration part spaces the coils at constant distances, and synchronize the coil currents to the bucket. In this section, the acceleration increases as the velocity increases, up to the maximum that the bucket can take. After that, the constant acceleration region begins. This region spaces the coils at increasing distances to give a fixed amount of velocity increase per unit of time.

In this mode, the major proposal for use of mass-drivers was to transport lunar surface material to space habitats so that it could be processed using solar energy. The Space Studies Institute showed that this application was reasonably practical.

In the prototypes, the payload would be held in a bucket and then released, so that the bucket can be decelerated and reused. A disposable bucket, on the other hand, would avail acceleration along the whole track.

On Earth

In contrast to a space gun, a mass driver can have a length of hundreds of kilometers and therefore reach target velocity without excessive g forces to the passengers. It can be constructed as a very long and mainly horizontally aligned launch track for spacelaunch, targeted upwards at the end, partly by bending of the track upwards and partly by Earth's curvature in the other direction.

Natural elevations, such as mountains, may facilitate the construction of the distant, upwardly targeted part. The higher up the track terminates, the less resistance from the atmosphere the launched object will receive.

By being mainly located slightly above, on or beneath the ground, a mass driver may be easier to maintain compared with many other structures of non-rocket spacelaunch. If not underground then it still needs to be housed in a pipe that is constantly vacuum pumped in order to reduce drag.

In order to be able to launch humans and delicate instruments, it would need to be several hundreds of kilometres long. For rugged objects, with magnetic assistance, a significantly smaller, circular, track may suffice.

A mass driver on Earth would be a compromise system. A mass driver would accelerate a payload up to some high speed which would not be high enough for orbit. It would then release the payload, which would complete the launch with rockets. This would drastically reduce the amount of velocity needed to be provided by rockets to reach orbit. On Earth, a mass driver design could possibly use well-tested maglev components.

Spacecraft-based mass drivers

A spacecraft could carry a mass driver as its primary engine. With a suitable source of electrical power (probably a nuclear reactor) the spaceship could then use the mass driver to accelerate pieces of matter of almost any sort, boosting itself in the opposite direction. At the smallest scale of reaction mass, this type of drive is called an ion drive.

No theoretical limit is known for the size, acceleration or muzzle energy of linear motors. However, at higher muzzle velocities, energetic efficiency is inevitably very poor. While linear motors can, with current technology, convert up to about 50% of the electrical energy into kinetic energy of the projectile, the energy of interest is the kinetic energy of the vehicle, and as the muzzle velocity increases, this is a smaller and smaller percentage of the generated power.

Since kinetic energy of the projectile is $\frac{1}{2}mv^2$, the energy requirements vary with the square of the specific impulse, so in a design one must choose a tradeoff between energy consumption and consumption of reaction mass. In addition, since momentum of a particle of mass m has momentum mv- proportional to velocity, but energy is a square law, so the average thrust for a given energy is inversely proportional to the velocity of the particles. In other words, heavier projectile masses give lower specific impulse but proportionately higher thrust.

Since a mass driver could use any type of mass for reaction mass to move the spacecraft, this, or some variation, seems ideal for deep-space vehicles that scavenge reaction mass from found resources.

One possible drawback of the mass driver is that it has the potential to send solid reaction mass travelling at dangerously high relative speeds into useful orbits and traffic lanes. To overcome this problem, most schemes plan to throw finely-divided dust. Alternately, liquid oxygen could be used as reaction mass, which upon release would boil down to its molecular state. Propelling the reaction mass to solar escape velocity is another way to ensure that it will not remain a hazard.

Space is almost completely empty, so propellant sources are only to be found at asteroids, comets, moons and planets.

Hybrid mass drivers

Another variation is to have a mass-driver on a spacecraft, and use it to "reflect" masses from a stationary mass-driver. Each deceleration and acceleration of the mass contributes to the momentum of the spacecraft. The spacecraft need not carry reaction mass, and doesn't even need much electricity, beyond the amount needed to replace losses in the electronics. The system could also be used to deliver pellets of fuel to the spacecraft for use in powering some other propulsion system. This could be considered a form of beam-powered propulsion.

Another theoretical use for this concept of propulsion can be found in space fountains, a system in which a continuous stream of pellets in a circular track holds up a tall (and heavy) structure.

Mass drivers as weapons

High-acceleration linear motors are currently undergoing active research by the military for use as (ground-based or ship-based) armor-piercing weapons. Since a mass driver is essentially a very large, very high-velocity linear motor, it could in principle be used as a very large weapon, either firing directly on a target in space, or used to attack a location on a planet's surface from a position in orbit, long range over-the-horizon indirect fire, or from a nearby planetary body, such as a moon.

Practical attempts

Prototype mass drivers have existed since 1976 (Mass Driver 1). Most were constructed by the US Space Studies Institute in order to prove their properties and practicality.

Chapter 12

Transrapid

Transrapid 09 at the Emsland test facility in Germany

Transrapid is a German high-speed monorail train using magnetic levitation. Based on a patent from 1934, planning of the Transrapid system started in 1969. The test facility for the system in Emsland, Germany was completed in 1987. In 1991, the technical readiness for application was approved by the Deutsche Bundesbahn in cooperation with renowned universities.

Its current application-ready version, the Transrapid 09, has been designed for 500 km/h cruising speed and allows acceleration and deceleration of approx. 1 m/s^2.

In 2004, the first commercial implementation was completed. The Shanghai Maglev Train connects the rapid transit network 30.5 km (19.0 mi) to the Shanghai Pudong International Airport. The Transrapid system has not yet been deployed on a long-distance intercity line.

The system is developed and marketed by Transrapid International, a joint venture of Siemens and ThyssenKrupp. Critical voices, such as Rod Eddington refer to recent developments of railway and other competing technologies and draw parallels between Transrapid and previous high technology hypes without broad market impact outside niche applications.

Technology

Levitation

The superspeed maglev system has no wheels, axles, transmissions, or pantographs. It does not roll, it hovers using the attractive magnetic force between the two linear arrays of electromagnetic coils - one side in the vehicle, the other in the guideway - that function as a magnetic dipole. Electronic systems measuring the distance at 100 kHz frequency guarantee that the clearance between the coils attached to the underside of the guideway and the magnetic portion of the vehicle wrapped around the guideway edges remains constant (nominally 10 mm). When levitated, the vehicle has about 15 centimeters of clearance over the guideway surface. The Transrapid requires less power to hover than it needs to run its air conditioning equipment. The levitation system and all on board electronics are supplied by the power recovered from harmonic oscillations of magnetic field of the track's linear stator (those oscillations being parasitic cannot be used for propulsion) at speeds above 80 km/h, while at lower speeds power was obtained through physical connections to the track up to version TR08; this new energy transmission has been developed for TR09 so that the trainset no longer needs physical contact at any speeds. In case of power failure of the track's propulsion system, the car can use on-board backup batteries to power the levitation system.

Propulsion

The Transrapid maglev system uses a synchronous *longstator* linear motor for both propulsion and braking. It works like a rotating electric motor whose stator is "unrolled" along the underside of the guideway, so that instead of producing a torque (rotation) it produces a linear force along its length. The electromagnets in the vehicle that lift it also work as the equivalent of the excitation portion (rotor). Since the magnetic traveling field only works in one direction, if there were several trains on the track section, they would travel in the same direction, making collisions between moving trains less likely.

Energy requirements

The normal energy consumption of the Transrapid is approximately 50–100 kW per section for levitation and travel, and vehicle control. The drag coefficient of the Transrapid is about 0.26. The air resistance of the vehicle, which has a frontal cross section of 16 m², requires a power consumption, at 400 km/h (111 m/s) cruising speed, given by the following formula:

$$P = c_w \cdot A_{\text{Front}} \cdot v^3 \cdot (\text{density of surrounding air})/2$$

$$\begin{aligned} P &= 0.26 \cdot 16\,\text{m}^2 \cdot (111\,\text{m/s})^3 \cdot 1.24\,\text{kg/m}^3/2 \\ P &= 3.53 \cdot 10^6\,\text{kg} \cdot \text{m}^2/\text{s}^3 = 3.53 \cdot 10^6\,\text{N} \cdot \text{m/s} = 3.53\,\text{MW} \end{aligned}$$

Power consumption compares favorably with other high-speed rail systems. With an efficiency of 0.85, the power required is about 4.2 MW. Energy consumption for levitation and guidance purposes equates to approximately 1.7 kW/t. As the propulsion system is also capable of functioning in reverse, energy is transferred back into the electricity network during braking. An exception to this is when an emergency stop is performed using the emergency landing skids beneath the vehicle, although this method of bringing the vehicle to a stop is intended only as a last resort should it be impossible or undesirable to keep the vehicle levitating on back-up power to a natural halt.

Market segment, ecological impact and historical parallels

Compared to classical railway lines, Transrapid allows higher speeds and gradients with lower wear and tear and even lower energy consumption and maintenance needs. The Transrapid track is more flexible, and therefore more easily adapted to specific geographical circumstances than a classical train system. Cargo is restricted to a maximum payload of 15 metric tonnes per car. Transrapids allows maximum speeds of 550 km/h, placing it between conventional High Speed Trains (200–320 km/h) and Air Traffic (720–990 km/h). The magnetic field generator, an important part of the engine being a part of the track, limits the system capacity.

From a competition standpoint, the Transrapid is a proprietary solution. The track being a part of the engine, only the single-source Transrapid vehicles and infrastructure can be operated. There is no multisourcing foreseen concerning vehicles or the highly complicated crossings and switches. Unlike classical railways or other infrastructure networks (as jointly administrated by the Bundesnetzagentur in Germany) a Transrapid system does not allow any direct competition.

Ecological impact

The Transrapid itself is an electrically driven, clean, high-speed, high-price, high-capacity means of transport able to build up point-to-point passenger connections in geographically challenged surroundings. This has to be set in comparison with the impact on heritage and or landscape protection areas (compare Waldschlößchenbrücke). Any impact of emissions has to take into account the source of electrical energy. The reduced expense, noise and vibration of a people-only Transrapid versus a cargo train track is not directly comparable. The reuse of existing tracks and the interfacing with existing networks is limited. The Transrapid indirectly competes for resources, space and tracks in urban and city surroundings with classical urban transport systems and high speed trains.

Implementations

German high-speed competition

The Transrapid originated as one of several competing concepts for new land-based high speed public transportation developed in Germany. It also faced competition from the InterCityExpress (ICE), a high-speed rail system based on "traditional" railway technology. The ICE “won” in that it was adopted nationwide in Germany. A variety of studies for possible Transrapid systems was elaborated, including a long-distance line from Hamburg to Berlin. The last left was an airport connection track from Munich city to the Airport, which was finally canceled in early 2008 due to dramatically increasing cost projections.

China

Transrapid magnetic levitation train in Shanghai, connecting the subway station to Pudong International Airport

The only commercial implementation so far was in the year 2000, when the Chinese government ordered a Transrapid track to be built connecting Shanghai to its Pudong International Airport. It was inaugurated in 2002 and regular daily trips started in March 2004. The travel speed is 430 km/h, which the Maglev train maintains for 50 seconds as the short, 30.5 km (19.0 mi), track only allows the cruising speed to be maintained for a short time before deceleration must begin. The average number of riders per day (14 hours of operation) is about 7,500, while the maximum seating capacity per train is 440. A second class ticket price of about 50 RMB (Renminbi) (about 5 Euro) is four times the price of the Airport Bus and ten times more expensive than a comparable Underground ticket.

The project was sponsored by the German Hermes loans with DM 200 million. The total cost is believed to be $1.33 billion.

A controversial planned extension of the line to Shanghai Hongqiao Airport (35 km) and onward to the city of Hangzhou (175 km) has been repeatedly delayed. Originally planned to be ready for Expo 2010, final approval was granted on August 18, 2008, and construction is now scheduled to start in 2010 for completion in 2014.

Germany

A 40-kilometre (25 mi) project between Munich Central Station and Munich Airport was close to being built, but was canceled on 27 March 2008, when the German government scrapped the Transrapid project because of a massive overrun in costs. Prior to the cancellation, the Bavarian governing party CSU faced internal and local resistance, in particular from communities along the proposed route. The CSU had planned to position Transrapid as an example of future technology and innovation in Bavaria. German federal transport minister Wolfgang Tiefensee announced the decision after a crisis meeting in Berlin at which industry representatives reportedly revealed that costs had risen from €1.85 billion to well over €3 billion ($4.7 billion). This rise in projected costs, however was mostly due to the cost estimates of the construction of the tunnel and related civil engineering after the designated operator Deutsche Bahn AG shifted most of the risk-sharing towards its subcontractors - and not due to the cost of the maglev technology.

Iran

In 2007 Iran and a German company reached an agreement on using maglev trains to link the cities of Tehran and Mashhad. The agreement was signed at the Mashhad International Fair site between Iranian Ministry of Roads and Transportation and the German company. Maglev trains can reduce the 900 km travel time between Tehran and Mashhad to about 2.5 hours. Munich-based Schlegel Consulting Engineers said they had signed the contract with the Iranian ministry of transport and the governor of Mashad. "We have been mandated to lead a German consortium in this project," a spokesman said. "We are in a preparatory phase." The next step will be assemble a consortium, a process that is expected to take place "in the coming months," the spokesman said. The project could be worth between 10 billion and 12 billion euros, the Schlegel spokesman said. Siemens and ThyssenKrupp, the developers of a high-speed maglev train, called the Transrapid, both said they were unaware of the proposal. The Schlegel spokesman said Siemens and ThyssenKrupp were currently "not involved" in the consortium.

United Kingdom

The Transrapid was considered by the UK government for a 500 km/h (310 mph) link between London and Glasgow, via Birmingham, Liverpool/Manchester, Leeds, Teesside, Newcastle and Edinburgh, but was rejected in July 2007.

Projects elsewhere

Several European projects have been studied, but so far classical rail has been the preferred solution.

There have been several evaluations conducted in the USA. Again, so far, classical railway remains the suggested solution. No actual project has been started yet.

There have been initial talks for a project in the Persian Gulf region, connecting Bahrain – Qatar – UAE.

Incidents

September 2006 accident

On 22 September 2006, a Transrapid train collided with a maintenance vehicle at 170 km/h on the test track in Lathen. The maintenance vehicle destroyed the first section of the train, and came to rest on its roof. This was the first major accident involving a Transrapid train. The news media reported 23 fatalities and that several people were severely injured, these being the first fatalities on any maglev. The accident was caused by human error with the first train being allowed to leave the station before the maintenance vehicle had moved off the track. This situation is avoided in a production environment by installing an automatic collision avoidance system.

SMT fire accident

On 11 August 2006, a Transrapid train running on Shanghai Maglev Line caught fire. The fire was quickly put out by Shanghai's firemen. It was reported that the vehicle's on-board batteries may have caused the fire.

Alleged theft of Transrapid technology

In April 2006, new announcements by Chinese officials planning on cutting maglev rail costs by a third have stirred some strong comments by various German officials and more diplomatic statements of concern from Transrapid officials. The Deutsche Welle reports that the China Daily quoted the State Council encouraging engineers to "learn and absorb foreign advanced technologies while making further innovations."

The China Aviation Industry Corporation said in their defense that the new Zhui Feng maglev train is not based or dependent on foreign technology. They claim it is not only a much lighter train, but also has a much more advanced design.

Chapter 13

Maglev (Transport)

JR-Maglev at Yamanashi, Japan test track in November, 2005

Transrapid 09 at the Emsland test facility in Germany

Maglev (derived from magnetic levitation), is a system of transportation that suspends, guides and propels vehicles, predominantly trains, using magnetic levitation from a very large number of magnets for lift and propulsion. This method has the potential to be faster, quieter and smoother than wheeled mass transit systems. The power needed for levitation is usually not a particularly large percentage of the overall consumption; most of the power used is needed to overcome air drag, as with any other high speed train.

The highest recorded speed of a Maglev train is 581 kilometres per hour (361 mph), achieved in Japan in 2003, only 6 kilometres per hour (3.7 mph) faster than the conventional TGV wheel-rail speed record.

The first commercial maglev people mover was simply called "MAGLEV" and officially opened in 1984 near Birmingham, England. It operated on an elevated 600-metre (2,000 ft) section of monorail track between Birmingham International Airport and Birmingham International railway station, running at speeds up to 42 km/h (26 mph); the system was eventually closed in 1995 due to reliability problems.

Perhaps the most well known implementation of high-speed maglev technology currently operating commercially is the Shanghai Maglev Train, an IOS (initial operating segment) demonstration line of the German-built Transrapid train in Shanghai, China that transports people 30 km (19 mi) to the airport in just 7 minutes 20 seconds, achieving a top speed of 431 km/h (268 mph), averaging 250 km/h (160 mph).

History

First patents

High speed transportation patents were granted to various inventors throughout the world. Early United States patents for a linear motor propelled train were awarded to the inventor, Alfred Zedekiah (German). The inventor was awarded U.S. Patent 782,312 (June 21, 1907) and U.S. Patent RE12,700 (August 21, 1907). In 1907, another early electromagnetic *transportation system* was developed by F. S. Smith. A series of German patents for magnetic levitation trains propelled by linear motors were awarded to Hermann Kemper between 1937 and 1941. An early modern type of maglev train was described in U.S. Patent 3,158,765, *Magnetic system of transportation*, by G. R. Greenfly (August 25, 1959). The first use of "maglev" in a United States patent was in "*Magnetic levitation guidance*" by Canadian Patents and Development Limited

Development

In the late 1940s, Professor Eric Laithwaite of Imperial College in London developed the first full-size working model of the linear induction motor. He became professor of heavy electrical engineering at Imperial College in 1964, where he continued his successful development of the linear motor. As the linear motor does not require physical contact between the vehicle and guideway, it became a common fixture on many advanced transportation systems being developed in the 1960s and 70s. Laithwaite himself joined development of one such project, the Tracked Hovercraft, although funding for this project was cancelled in 1973.

The linear motor was naturally suited to use with maglev systems as well. In the early 1970s, Laithwaite discovered a new arrangement of magnets that allowed a single linear motor to produce both lift as well as forward thrust, allowing a maglev system to be built with a single set of magnets. Working at the British Rail Research Division in Derby, along with teams at several civil engineering firms, the "traverse-flux" system was developed into a working system.

New York, United States 1968

In 1961, when he was delayed during rush hour traffic on the Throgs Neck Bridge, James Powell, a researcher at Brookhaven National Laboratory (BNL), thought of using magnetically levitated transportation to solve the traffic problem. Powell and BNL colleague Gordon Danby jointly worked out a MagLev concept using static magnets mounted on a moving vehicle to induce electrodynamic lifting and stabilizing forces in specially shaped loops on a guideway.

Hamburg, Germany 1979

Transrapid 05 was the first maglev train with longstator propulsion licensed for passenger transportation. In 1979, a 908 m track was opened in Hamburg for the first International

Transportation Exhibition (IVA 79). There was so much interest that operations had to be extended three months after the exhibition finished, having carried more than 50,000 passengers. It was reassembled in Kassel in 1980.

Birmingham, United Kingdom 1984–1995

The world's first commercial automated maglev system was a low-speed maglev shuttle that ran from the airport terminal of Birmingham International Airport to the nearby Birmingham International railway station between 1984–1995. The length of the track was 600 meters (1,969 ft), and trains "flew" at an altitude of 15 millimeters (0.6 in), levitated by electromagnets, and propelled with linear induction motors. It was in operation for nearly eleven years, but obsolescence problems with the electronic systems made it unreliable in its later years. One of the original cars is now on display at Railworld in Peterborough, while the RTV31 hover train vehicle is preserved on the Nene Valley Railway in Peterborough.

Several favourable conditions existed when the link was built:

- The British Rail Research vehicle was 3 tonnes and extension to the 8 tonne vehicle was easy.
- Electrical power was easily available.
- The airport and rail buildings were suitable for terminal platforms.
- Only one crossing over a public road was required and no steep gradients were involved.
- Land was owned by the railway or airport.
- Local industries and councils were supportive.
- Some government finance was provided and because of sharing work, the cost per organization was not high.

After the original system closed in 1995, the original guideway lay dormant. The guideway was reused in 2003 when the replacement cable-hauled AirRail Link Cable Liner people mover was opened.

Japan 1985-

JNR ML500 at Miyazaki, Japan test track on 21 December 1979. 517km/h. Guinness World Records authorization at that time.

In Japan, there are two independently developed Maglev trains. One is HSST by Japan Airlines and the other, which is more well-known, is JR-Maglev by Japan Railways Group. The development of the latter started in 1969, and Miyazaki test track had regularly hit 517 km/h by 1979 but, after an accident that destroyed the train, a new design was decided upon. Tests through the 1980s continued in Miyazaki before transferring a far larger and elaborate test track (20 km long) in Yamanashi in 1997. In that year, development of HSST started in 1974, based on technologies introduced from Germany. In Tsukuba, Japan (1985), the HSST-03 (Linimo) wins popularity in spite of being 30 km/h slower at the Tsukuba World Exposition. In Okazaki, Japan (1987), the JR-Maglev took a test ride at the Okazaki exhibition. In Saitama, Japan (1988), the HSST-04-1 was revealed at the Saitama exhibition performed in Kumagaya. Its fastest recorded speed was 30 km/h. In Yokohama, Japan (1989), the HSST-05 acquires a business driver's license at Yokohama exhibition and carries out general test ride driving. Maximum speed 42 km/h. JR-Maglev features 10 centimeter float (approx. 3.9 inch) above the guideway.

Vancouver, Canada, and Hamburg, Germany 1986-1988

In Vancouver, Canada (1986), the JR-Maglev was exhibited at Expo 86. Guests could ride the train along a short section of track at the fairgrounds. In Hamburg, Germany (1988), the TR-07 in international traffic exhibition (IVA88) performed Hamburg.

Berlin, Germany 1989–1991

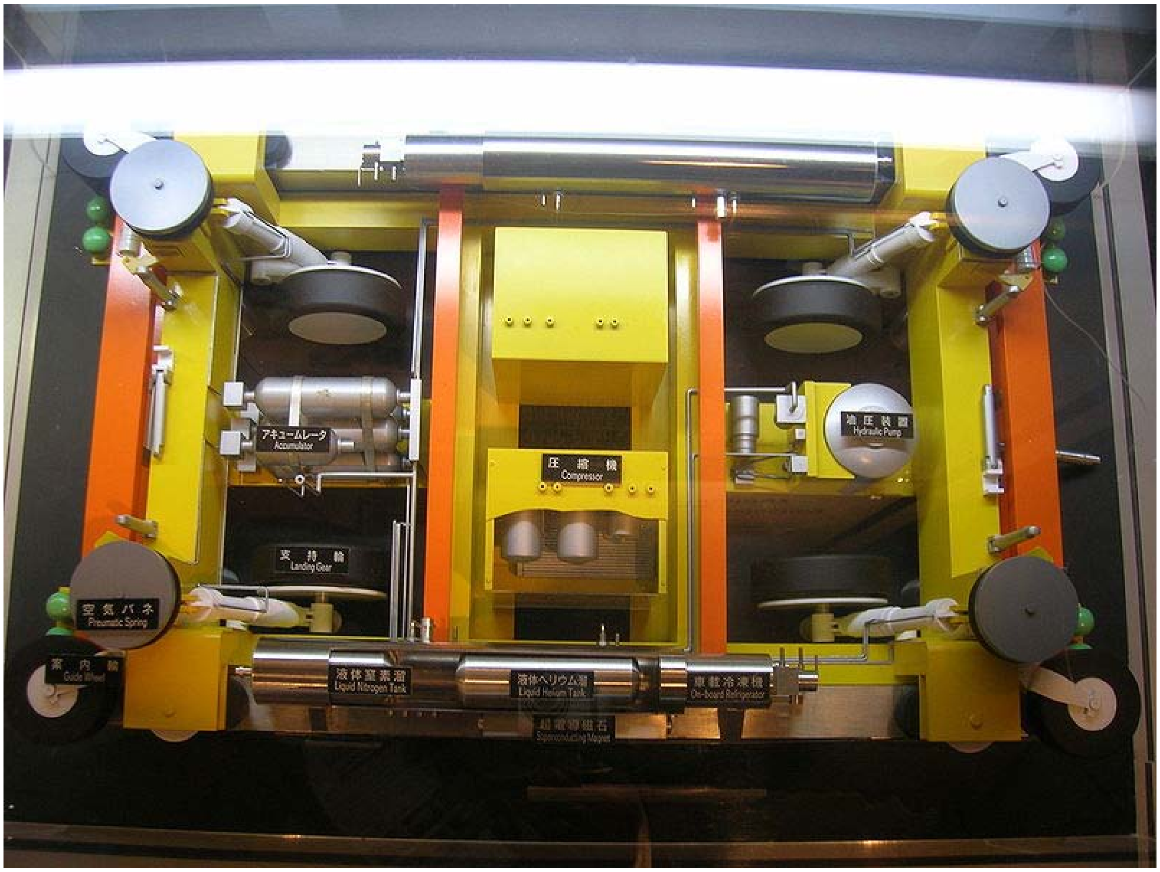
In West Berlin, the M-Bahn was built in the late 1980s. It was a driverless maglev system with a 1.6 km track connecting three stations. Testing in passenger traffic started in August 1989, and regular operation started in July 1991. Although the line largely followed a new elevated alignment, it terminated at the U-Bahn station Gleisdreieck, where it took over a platform that was then no longer in use; it was from a line that formerly ran to East Berlin. After the fall of the Berlin Wall, plans were set in motion to reconnect this line (today's U2). Deconstruction of the M-Bahn line began only two months after regular service began that was called Pundai project and was completed in February 1992.

Other patents

High speed transportation patents were also granted to various other inventors throughout the world. Early United States patents for a linear motor propelled train were awarded to the inventor, Alfred Zehden (German). The inventor was awarded U.S. Patent 782,312 (June 21, 1902) and U.S. Patent RE12,700 (August 21, 1907). In 1907, another early electromagnetic *transportation system* was developed by F. S. Smith. A series of German patents for magnetic levitation trains propelled by linear motors were awarded to Hermann Kemper between 1937 and 1941. An early modern type of maglev train was described in U.S. Patent 3,158,765, *Magnetic system of transportation*, by G. R. Polgreen (August 25, 1959). The first use of "maglev" in a United States patent was in "*Magnetic levitation guidance*" by Canadian Patents and Development Limited.

Technology

Overview



MLX01 maglev train Superconducting magnet Bogie

The term "maglev" refers not only to the vehicles, but to the railway system as well, specifically designed for magnetic levitation and propulsion. All operational implementations of maglev technology have had minimal overlap with wheeled train technology and have not been compatible with conventional rail tracks. Because they cannot share existing infrastructure, these maglev systems must be designed as complete transportation systems. The Applied Levitation SPM Maglev system is inter-operable with steel rail tracks and would permit maglev vehicles and conventional trains to operate at the same time on the same right of way. MAN in Germany also designed a maglev system that worked with conventional rails, but it was never fully developed.

There are two particularly notable types of maglev technology:

- For electromagnetic suspension (EMS), electromagnets in the train attract it to a magnetically conductive (usually steel) track.
- Electrodynamic suspension (EDS) uses electromagnets on both track and train to push the train away from the rail.

Another experimental technology, which was designed, proven mathematically, peer reviewed, and patented, but is yet to be built, is the magnetodynamic suspension (MDS), which uses the attractive magnetic force of a permanent magnet array near a steel track to lift the train and hold it in place. Other technologies such as repulsive permanent magnets and superconducting magnets have seen some research.

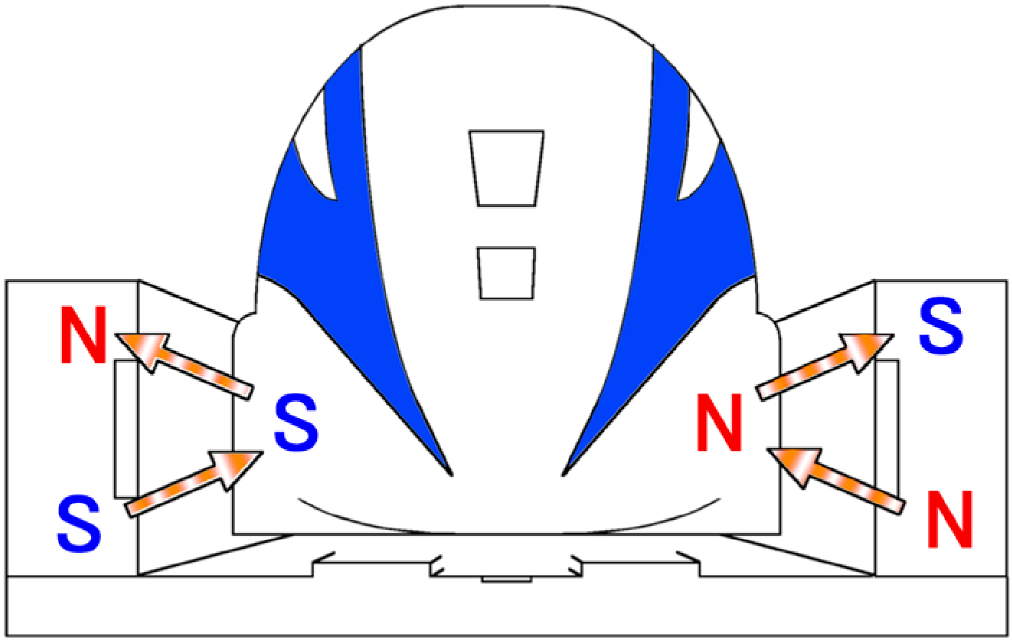
Electromagnetic suspension

In current electromagnetic suspension (EMS) systems, the train levitates above a steel rail while electromagnets, attached to the train, are oriented toward the rail from below. The system is typically arranged on a series of C-shaped arms, with the upper portion of the arm attached to the vehicle, and the lower inside edge containing the magnets. The rail is situated between the upper and lower edges.

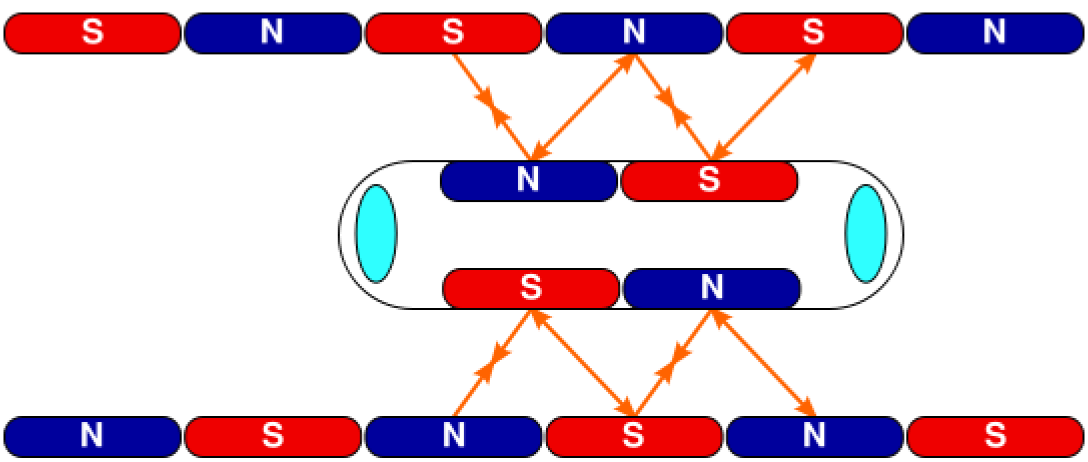
Magnetic attraction varies inversely with the cube of distance, so minor changes in distance between the magnets and the rail produce greatly varying forces. These changes in force are dynamically unstable - if there is a slight divergence from the optimum position, the tendency will be to exacerbate this, and complex systems of feedback control are required to maintain a train at a constant distance from the track, (approximately 15 millimeters (0.6 in)).

The major advantage to suspended maglev systems is that they work at all speeds, unlike electrodynamic systems which only work at a minimum speed of about 30 km/h. This eliminates the need for a separate low-speed suspension system, and can simplify the track layout as a result. On the downside, the dynamic instability of the system demands high tolerances of the track, which can offset, or eliminate this advantage. Laithwaite, highly skeptical of the concept, was concerned that in order to make a track with the required tolerances, the gap between the magnets and rail would have to be increased to the point where the magnets would be unreasonably large. In practice, this problem was addressed through increased performance of the feedback systems, which allow the system to run with close tolerances.

Electrodynamic suspension



JR-Maglev EDS suspension is due to the magnetic fields induced either side of the vehicle by the passage of the vehicles superconducting magnets.



EDS Maglev Propulsion via propulsion coils

In electrodynamic suspension (EDS), both the rail and the train exert a magnetic field, and the train is levitated by the repulsive force between these magnetic fields. The magnetic field in the train is produced by either superconducting magnets (as in JR-Maglev) or by an array of permanent magnets (as in Inductrack). The repulsive force in the track is created by an induced magnetic field in wires or other conducting strips in the track. A major advantage of the repulsive maglev systems is that they are naturally stable - minor *narrowing* in distance between the track and the magnets creates strong forces to repel the magnets back to their original position, while a slight increase in distance greatly reduces the force and again returns the vehicle to the right separation. No feedback control is needed.

Repulsive systems have a major downside as well. At slow speeds, the current induced in these coils and the resultant magnetic flux is not large enough to support the weight of the train. For this reason the train must have wheels or some other form of landing gear to support the train until it reaches a speed that can sustain levitation. Since a train may stop at any location, due to equipment problems for instance, the entire track must be able to support both low-speed and high-speed operation. Another downside is that the repulsive system naturally creates a field in the track in front and to the rear of the lift magnets, which act against the magnets and create a form of drag. This is generally only a concern at low speeds, at higher speeds the effect does not have time to build to its full potential and other forms of drag dominate.

The drag force can be used to the electrodynamic system's advantage, however, as it creates a varying force in the rails that can be used as a reactionary system to drive the train, without the need for a separate reaction plate, as in most linear motor systems. Laithwaite led development of such "traverse-flux" systems at his Imperial College laboratory. Alternately, propulsion coils on the guideway are used to exert a force on the magnets in the train and make the train move forward. The propulsion coils that exert a force on the train are effectively a linear motor: an alternating current flowing through the coils generates a continuously varying magnetic field that moves forward along the track. The frequency of the alternating current is synchronized to match the speed of the train. The offset between the field exerted by magnets on the train and the applied field creates a force moving the train forward.

Pros and cons of different technologies

Each implementation of the magnetic levitation principle for train-type travel involves advantages and disadvantages.

Technology	*Pros*	*Cons*
EMS (Electromagnetic suspension)	Magnetic fields inside and outside the vehicle are less than EDS; proven, commercially available technology that can attain very high speeds (500 km/h); no wheels or secondary propulsion system needed	The separation between the vehicle and the guideway must be constantly monitored and corrected by computer systems to avoid collision due to the unstable nature of electromagnetic attraction; due to the system's inherent instability and the required constant corrections by outside systems, vibration issues may

		occur.
EDS (Electrodynamic suspension)	Onboard magnets and large margin between rail and train enable highest recorded train speeds (581 km/h) and heavy load capacity; has recently demonstrated (December 2005) successful operations using high temperature superconductors in its onboard magnets, cooled with inexpensive liquid nitrogen	Strong magnetic fields onboard the train would make the train inaccessible to passengers with pacemakers or magnetic data storage media such as hard drives and credit cards, necessitating the use of magnetic shielding; limitations on guideway inductivity limit the maximum speed of the vehicle; vehicle must be wheeled for travel at low speeds.
Inductrack System (Permanent Magnet EDS)	Failsafe Suspension - no power required to activate magnets; Magnetic field is localized below the car; can generate enough force at low speeds (around 5 km/h) to levitate maglev train; in case of power failure cars slow down on their own safely; Halbach arrays of permanent magnets may prove more cost-effective than electromagnets	Requires either wheels or track segments that move for when the vehicle is stopped. New technology that is still under development (as of 2008) and as yet has no commercial version or full scale system prototype.

Neither Inductrack nor the Superconducting EDS are able to levitate vehicles at a standstill, although Inductrack provides levitation down to a much lower speed; wheels are required for these systems. EMS systems are wheel-less.

The German Transrapid, Japanese HSST (Linimo), and Korean Rotem EMS maglevs levitate at a standstill, with electricity extracted from guideway using power rails for the latter two, and wirelessly for Transrapid. If guideway power is lost on the move, the Transrapid is still able to generate levitation down to 10 km/h (6.2 mph) speed, using the power from onboard batteries. This is not the case with the HSST and Rotem systems.

Propulsion

An EDS system can provide both levitation and propulsion using an onboard linear motor. EMS systems can only levitate the train using the magnets onboard, not propel it forward. As such, vehicles need some other technology for propulsion. A linear motor (propulsion coils) mounted in the track is one solution. Over long distances where the cost of propulsion coils could be prohibitive, a propeller or jet engine could be used.

Stability

Earnshaw's theorem shows that any combination of static magnets cannot be in a stable equilibrium. However, the various levitation systems achieve stable levitation by violating the assumptions of Earnshaw's theorem. Earnshaw's theorem assumes that the magnets are static and unchanging in field strength and that the relative permeability is constant and greater than unity everywhere. EMS systems rely on active electronic stabilization. Such systems constantly measure the bearing distance and adjust the electromagnet current accordingly. All EDS systems are moving systems (no EDS system can levitate the train unless it is in motion).

Because Maglev vehicles essentially fly, stabilisation of pitch, roll and yaw is required by magnetic technology. In addition translations, surge (forward and backward motions), sway (sideways motion) or heave (up and down motions) can be problematic with some technologies.

If superconducting magnets are used on a train above a track made out of a permanent magnet, then the train would be locked in to its lateral position on the track. It can move linearly along the track, but not off the track. This is due to the Meissner Effect.

Guidance

Some systems use Null Current systems (also sometimes called Null Flux systems); these use a coil which is wound so that it enters two opposing, alternating fields, so that the average flux in the loop is zero. When the vehicle is in the straight ahead position, no current flows, but if it moves off-line this creates a changing flux that generates a field that pushes it back into line. However, some systems use coils that try to remain as much as possible in the null flux point between repulsive magnets, as this reduces eddy current losses.

Evacuated tubes

Some systems (notably the swissmetro system) propose the use of vactrains — maglev train technology used in evacuated (airless) tubes, which removes air drag. This has the potential to increase speed and efficiency greatly, as most of the energy for conventional Maglev trains is lost in air drag.

One potential risk for passengers of trains operating in evacuated tubes is that they could be exposed to the risk of cabin depressurization unless tunnel safety monitoring systems can repressurize the tube in the event of a train malfunction or accident. The Rand Corporation has designed a vacuum tube train that could, in theory, cross the Atlantic or the USA in 20 minutes.

Power and energy usage

Energy for maglev trains is used to accelerate the train, and may be regained when the train slows down ("regenerative braking"). It is also used to make the train levitate and to stabilise the movement of the train. The main part of the energy is needed to force the train through the air ("air drag"). Also some energy is used for air conditioning, heating, lighting and other miscellaneous systems.The maglev trains are powered on electromagnetism.

At very low speeds the percentage of power (energy per time) used for levitation can be significant. Also for very short distances the energy used for acceleration might be considerable. But the power used to overcome air drag increases with the cube of the velocity, and hence dominates at high speed (note: the energy needed per mile increases by the square of the velocity and the time decreases linearly.).

Advantages and disadvantages

Compared to conventional trains

Major comparative differences exist between the two technologies. First of all, maglevs are not trains, they are non-contact electronic transport systems, not mechanical friction-reliant rail systems. Their differences lie in maintenance requirements and the reliability of electronic versus mechanically based systems, all-weather operations, backward-compatibility, rolling resistance, weight, noise, design constraints, and control systems.

- **Maintenance Requirements Of Electronic Versus Mechanical Systems**: Maglev trains currently in operation have demonstrated the need for nearly insignificant guideway maintenance. Their electronic vehicle maintenance is minimal and more closely aligned with aircraft maintenance schedules based on hours of operation, rather than on speed or distance traveled. Traditional rail is subject to the wear and tear of miles of friction on mechanical systems and increases exponentially with speed, unlike maglev systems. This basic difference is the huge cost difference between the two modes and also directly affects system reliability, availability and sustainability.

- **All-Weather Operations**: Maglev trains currently in operation are not stopped, slowed, or have their schedules affected by snow, ice, severe cold, rain or high winds. This cannot be said for traditional friction-based rail systems. Also, maglev vehicles accelerate and decelerate faster than mechanical systems regardless of the slickness of the guideway or the slope of the grade because they are non-contact systems.

- **Backwards Compatibility**: Maglev trains currently in operation are not compatible with conventional track, and therefore require all new infrastructure for their entire route, but this is not a negative if high levels of reliability and low operational costs are the goal. By contrast conventional high speed trains such as the TGV are able to run at reduced speeds on existing rail infrastructure, thus reducing expenditure where new infrastructure would be particularly expensive (such as the final approaches to city terminals), or on extensions where traffic does not justify new infrastructure. However, this "shared track approach" ignores mechanical rail's high maintenance requirements, costs and disruptions to travel from periodic maintenance on these existing lines. The use of a completely separate maglev infrastructure more than pays for itself with dramatically higher levels of all-weather operational reliability and almost insignificant maintenance costs. So, maglev advocates would argue against rail backward compatibility and its concomitant high maintenance needs and costs.

- **Efficiency**: Due to the lack of physical contact between the track and the vehicle, maglev trains experience no rolling resistance, leaving only air resistance and electromagnetic drag, potentially improving power efficiency.

- **Weight**: The weight of the electromagnets in many EMS and EDS designs seems like a major design issue to the uninitiated. A strong magnetic field is required to levitate a maglev vehicle. For the Transrapid, this is about 56 watts per ton. Another path for levitation is the use of superconductor magnets to reduce the energy consumption of the electromagnets, and the cost of maintaining the field. However, a 50-ton Transrapid maglev vehicle can lift an additional 20 tons, for a total of 70 tones, which surprisingly does not consume an exorbitant amount of energy. Most energy use for the TRI is for propulsion and overcoming the friction of air resistance. At speeds over 100 mph, which is the point of a high-speed maglev, maglevs use less energy than traditional fast trains.

- **Noise**: Because the major source of noise of a maglev train comes from displaced air, maglev trains produce less noise than a conventional train at equivalent speeds. However, the psychoacoustic profile of the maglev may reduce this benefit: a study concluded that maglev noise should be rated like road traffic while conventional trains have a 5-10 dB "bonus" as they are found less annoying at the same loudness level.

- **Design Comparisons**: Braking and overhead wire wear have caused problems for the Fastech 360 railed Shinkansen. Maglev would eliminate these issues. Magnet reliability at higher temperatures is a countervailing comparative disadvantage, but new alloys and manufacturing techniques have resulted in magnets that maintain their levitational force at higher temperatures.

As with many technologies, advances in linear motor design have addressed the limitations noted in early maglev systems. As linear motors must fit within or straddle their track over the full length of the train, track design for some EDS and EMS maglev systems is challenging for anything other than point-to-point services. Curves must be gentle, while switches are very long and need care to avoid breaks in current. An SPM maglev system, in which the vehicle is permanently levitated over the tracks, can instantaneously switch tracks using electronic controls, with no moving parts in the track.

A prototype SPM maglev train has also navigated curves with radius equal to the length of the train itself, which indciates that a full-scale train should be able to navigate curves with the same or narrower radius as a conventional train.

- **Control Systems**: EMS Maglev needs very fast-responding control systems to maintain a stable height above the track; multiple redundancy is built into these systems in the event of component failure and the Transrapid system has still levitated and operated with fully 1/2 of its magnet control systems shut down. Other maglev systems not using EMS active control are still in the experimental stage, except for the Central Japan Railway's MLX-01 superconducting EDS repulsive maglev system that levitates 11 centimeters above its guideway.

Compared to aircraft

For many systems, it is possible to define a lift-to-drag ratio. For maglev systems these ratios can exceed that of aircraft (for example Inductrack can approach 200:1 at high speed, far higher than any aircraft). This can make maglev more efficient per kilometre. However, at high cruising speeds, aerodynamic drag is much larger than lift-induced drag. Jet transport aircraft take advantage of low air density at high altitudes to significantly reduce drag during cruise, hence despite their lift-to-drag ratio disadvantage, they can travel more efficiently at high speeds than maglev trains that operate at sea level (this has been proposed to be fixed by the vactrain concept). Aircraft are also more flexible and can service more destinations with provision of suitable airport facilities.

Unlike airplanes, maglev trains are powered by electricity and thus need not carry fuel. Aircraft fuel is a significant danger during takeoff and landing accidents. Also, electric trains emit little direct carbon dioxide emissions, especially when powered by nuclear or renewable sources, but more than aircraft if powered by fossil fuels.

Economics

The Shanghai maglev demonstration line cost US$1.2 billion to build. This total includes infrastructure capital costs such as ROW clearing, extensive pile driving, on-site guideway manufacturing, in-situ pier construction every 25 meters, a maintenance facility and vehicle yard, several switches, two stations, operations and control systems, power feed system, cables and inverters, and operational training. Ridership is not a primary focus of this demonstration line, since the Longyang Road station is on the outskirts of Shanghai. Once the line is extended to South Shanghai Train station and Hongqiao Airport station, ridership will be ample enough for the SMT to not only cover O&M costs, which it already does with its demonstration leg, but it will be able to generate significant revenue.

China aims to limit the cost of future construction extending the maglev line to approximately $18 million per kilometer through new guideway modular manufacturing and construction techniques.

The United States Federal Railroad Administration 2003 Draft Environmental Impact Statement for a proposed Baltimore-Washington Maglev project gives an estimated 2008 capital costs of US$4.361 billion for 39.1 miles, or US$111.5 million per mile (US$69.3 million per kilometer). The Maryland Transit Administration (MTA) conducted their own Environmental Impact Statement, and put the pricetag at US$4.9 billion for construction, and $53 million a year for operations.

The proposed Chūō Shinkansen maglev in Japan is estimated to cost approximately US$82 billion to build, with a route blasting long tunnels through mountains. A Tokaido maglev route replacing current Shinkansen would cost some 1/10 the cost, as no new tunnel blasting would be needed, but noise pollution issues would make it infeasible.

The only low-speed maglev (100 km/h) currently operational, the Japanese Linimo HSST, cost approximately US$100 million/km to build. Besides offering improved operation and maintenance costs over other transit systems, these low-speed maglevs provide ultra-high levels of operational reliability and introduce little noise and zero air pollution into dense urban settings.

As maglev systems are deployed around the world, experts expect construction costs to drop as new construction methods are innovated along with economies of scale.

History of maximum speed record by a trial run

- 1971 - West Germany - Prinzipfahrzeug - 90 km/h
- 1971 - West Germany -TR-02(TSST)- 164 km/h
- 1972 - Japan - ML100 – 60 km/h - (manned)
- 1973 - West Germany - TR04 - 250 km/h (manned)
- 1974 - West Germany - EET-01 - 230 km/h (unmanned)
- 1975 - West Germany - Komet - 401.3 km/h (by steam rocket propulsion, unmanned)
- 1978 - Japan - HSST-01 - 307.8 km/h (by supporting rockets propulsion, made in Nissan, unmanned)
- 1978 - Japan - HSST-02 - 110 km/h (manned)
- 1979-12-12 - Japan-ML-500R - 504 km/h (unmanned) It succeeds in operation over 500 km/h for the first time in the world.
- 1979-12-21 - Japan -ML-500R- 517 km/h (unmanned)
- 1987 - West Germany - TR-06 - 406 km/h (manned)
- 1987 - Japan - MLU001 - 400.8 km/h (manned)
- 1988 - West Germany - TR-06 - 412.6 km/h (manned)
- 1989 - West Germany - TR-07 - 436 km/h (manned)
- 1993 - Germany - TR-07 - 450 km/h (manned)
- 1994 - Japan - MLU002N - 431 km/h (unmanned)
- 1997 - Japan - MLX01 - 531 km/h (manned)
- 1997 - Japan - MLX01 - 550 km/h (unmanned)
- 1999 - Japan - MLX01 - 548 km/h (unmanned)

- 1999 - Japan - MLX01 - 552 km/h (manned/five formation). Guinness authorization.
- 2003 - China - Transrapid SMT (built in Germany) - 501.5 km/h (manned/three formation)
- 2003 - Japan - MLX01 - 581 km/h (manned/three formation). Guinness authorization.

Existing maglev systems

Testing tracks

San Diego, USA

General Atomics has a 120-meter test facility in San Diego, which is being used as the basis of Union Pacific's 8 km freight shuttle in Los Angeles. The technology is "passive" (or "permanent"), using permanent magnets in a halbach array for lift, and requiring no electromagnets for either levitation or propulsion. General Atomics has received $90 million in research funding from the federal government. They are also looking to apply their technology to high-speed passenger services.

Emsland, Germany

Transrapid at the Emsland test facility

Transrapid, a German maglev company, has a test track in Emsland with a total length of 31.5 km (19.6 mi). The single track line runs between Dörpen and Lathen with turning loops at each end. The trains regularly run at up to 420 km/h (260 mph). The construction of the test facility began in 1980 and finished in 1984.

JR-Maglev, Japan

Japan has a demonstration line in Yamanashi prefecture where test trains JR-Maglev MLX01 have reached 581 kilometres per hour (361 mph), slightly faster than any wheeled trains (the current TGV speed record is 574.8 kilometres per hour (357.2 mph).

These trains use superconducting magnets which allow for a larger gap, and repulsive-type electrodynamic suspension (EDS). In comparison Transrapid uses conventional electromagnets and attractive-type electromagnetic suspension (EMS). These "Superconducting Maglev Shinkansen", developed by the Central Japan Railway Company (JR Central) and Kawasaki Heavy Industries, are currently the fastest trains in the world, achieving a record speed of 581 kilometres per hour (361 mph) on December 2, 2003. Yamanashi Prefecture residents (and government officials) can sign up to ride this for free, and some 100,000 have done so already.

FTA's UMTD program

In the US, the Federal Transit Administration (FTA) Urban Maglev Technology Demonstration program has funded the design of several low-speed urban maglev demonstration projects. It has assessed HSST for the Maryland Department of Transportation and maglev technology for the Colorado Department of Transportation. The FTA has also funded work by General Atomics at California University of Pennsylvania to demonstrate new maglev designs, the MagneMotion M3 and of the Maglev2000 of Florida superconducting EDS system. Other US urban maglev demonstration projects of note are the LEVX in Washington State and the Massachusetts-based Magplane.

Southwest Jiaotong University, China

On 31 December 2000, the first crewed high-temperature superconducting maglev was tested successfully at Southwest Jiaotong University, Chengdu, China. This system is based on the principle that bulk high-temperature superconductors can be levitated or suspended stably above or below a permanent magnet. The load was over 530 kg (1166 lb) and the levitation gap over 20 mm (0.79 in). The system uses liquid nitrogen, which is very cheap, to cool the superconductor.

Operational systems servicing the public

Liniment (Tobu Kyuryo Line, Japan)

Linimo train approaching Banpaku Kinen Koen, towards Fujigaoka Station in March 2005

The commercial automated "Urban Maglev" system commenced operation in March 2005 in Aichi, Japan. This is the nine-station 8.9 km long Tobu-kyuryo Line, otherwise known as the Linimo. The line has a minimum operating radius of 75 m and a maximum gradient of 6%. The linear-motor magnetic-levitated train has a top speed of 100 kilometres per hour (62 mph). The line serves the local community as well as the Expo 2005 fair site. The trains were designed by the Chubu HSST Development Corporation, which also operates a test track in Nagoya.

Shanghai Magnet Train

A maglev train coming out of the Pudong International Airport.

Transrapid, in Germany, constructed the first operational high-speed conventional maglev railway in the world, the Shanghai Maglev Train from downtown Shanghai (Shanghai Metro) to the Pudong International Airport. It was inaugurated in 2002. The highest speed achieved on the Shanghai track has been 501 km/h (311 mph), over a track length of 30 km. Despite the speeds, the maglev has been criticised as having few stops and a questionable commercial success. Construction of an extension to Hangzhou was planned to be finished in 2010, but has been postponed in favour of a conventional high speed railway running at 350 km/h. The Shanghai municipal government was considering building the maglev line extension underground to allay the public's fears of electromagnetic pollution; this same report states that the final decision has to be approved by the National Development and Reform Commission.

Daejeon, South Korea

The first maglev utilizing electromagnetic suspension opened to public was HML-03, which was made by Hyundai Heavy Industries, for Daejeon Expo in 1993 after five years of research and manufacturing two prototypes; HML-01 and HML-02. Research for urban maglev using electromagnetic suspension began in 1994 by the government. The first urban maglev opened to public was UTM-02 in Daejeon on 21 April 2008 after 14 years of development and building one prototype; UTM-01. The urban maglev runs on 1 km track between Expo Park and National Science Museum. Meanwhile UTM-02 remarked an innovation by conducting the world's first ever maglev simulation. However UTM-02 is still the second prototype of a final model. The final UTM model of Rotem's urban maglev, UTM-03, is scheduled to debut at the end of 2012 in Incheon's Yeongjong island where Incheon International Airport is located.

Under construction

Old Dominion University

Track of less than a mile in length has been constructed at Old Dominion University in Norfolk, Virginia, USA. Although the system was initially built by AMT, problems caused the company to abandon the project and turn it over to the University. This system uses a "smart train, dumb track" that involves most of the sensors, magnets, and computation occurring on the train rather than the track. This system will cost less to build per mile than existing systems. The $14 million originally planned did not allow for completion. The system is currently not operational, but research has proved useful. In October 2006, the research team performed an unscheduled test of the car that went smoothly. The whole system, unfortunately, was removed from the power grid for nearby construction. In February 2009, the team was able to retest the sled, or bogie, and was again successful despite power outages on campus. Tests will continue, increasing both speed and distance. Meanwhile, ODU has partnered with a Massachusetts-based company to test another maglev train on its campus. MagneMotion Inc. is expected to bring its prototype maglev vehicle, which is about the size of a van, to the campus to test in early 2010.

AMT Test Track - Powder Springs, Georgia

The same principle is involved in the construction of a second prototype system in Powder Springs, Georgia, USA, by American Maglev Technology, Inc.

Applied Levitation/Fastransit Test Track - Santa Barbara, California

Applied Levitation, Inc. has built a levitating prototype on a short indoor track, and is now planning a quarter-mile outdoor track, with switches, in or near Santa Barbara.

Beijing S1 Line

The Beijing municipal government is building China's first low-speed maglev line using technology developed by Defense Technology University. This is the 10.2 km long S1-West commuter rail line, which, together with seven other conventional lines, saw construction began on Feb. 28, 2011. Top speed will be 105 km/hr. It is scheduled to be completed in two years.

Proposed systems

Many maglev systems have been proposed in various nations of North America, Asia, and Europe. Many are still in the early planning stages, or even mere speculation, as with the transatlantic tunnel. But a few of the following examples have progressed beyond that point.

Australia

Sydney-Illawarra Maglev Proposal

There is a current proposal for a Maglev route between Sydney and Wollongong.

The proposal came to prominence in the mid-1990s. The Sydney - Wollongong commuter corridor is the largest in Australia, with upwards of 20,000 people commuting from the Illawarra to Sydney for work each day. Current trains crawl along the dated Illawarra line, between the cliff face of the Illawarra escarpment and the Pacific Ocean, with travel times about two hours between Wollongong Station and Central. The proposed Maglev would cut travel times to 20 minutes.

Melbourne Maglev Proposal

The proposed Melbourne Maglev connecting the city of Geelong through Metropolitan Melbourne's outer suburban growth corridors, Tullamarine and Avalon domestic in and international terminals in under 20 mins and on to Frankston, Victoria in under 30 minutes.

In late 2008, a proposal was put forward to the Government of Victoria to build a privately funded and operated Maglev line to service the Greater Melbourne metropolitan area in response to the Eddington Transport Report which neglected to investigate above ground transport options. The Maglev would service a population of over 4 million and the proposal was costed at A$8 billion.

However despite relentless road congestion and the highest roadspace per capita Australia, the government quickly dismissed the proposal in favour of road expansion including an A$8.5 billion road tunnel, $6 billion extension of the Eastlink to the Western Ring Road and a $700 million Frankston Bypass.

United Kingdom

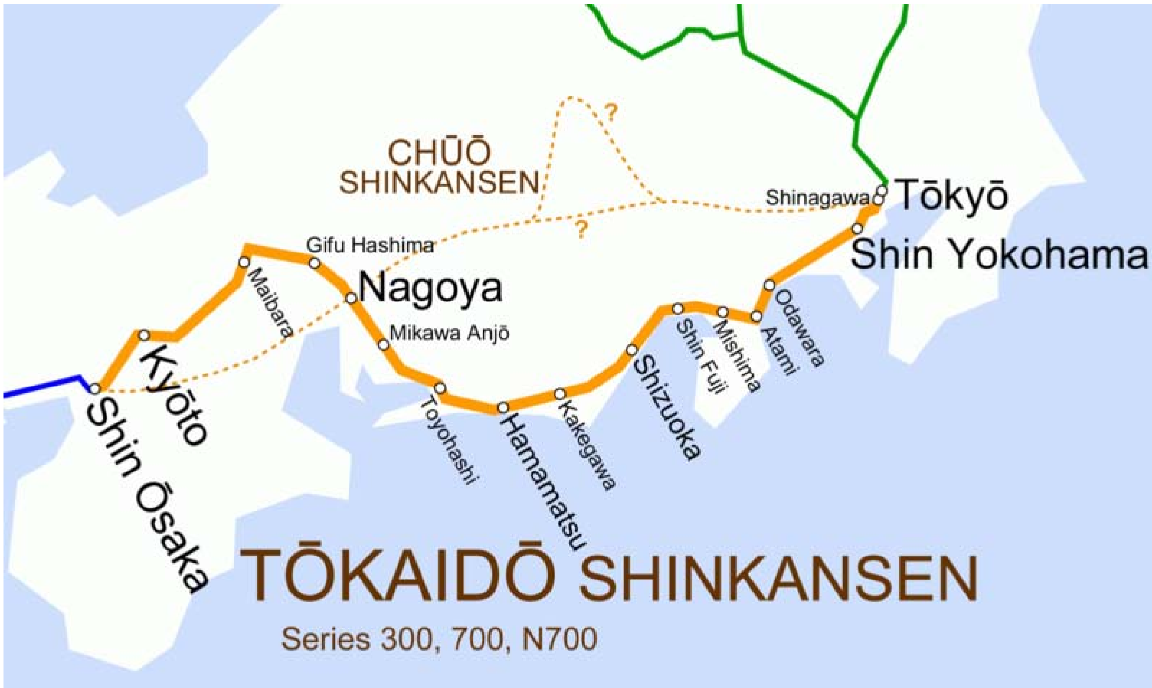
London – Glasgow: A maglev line was recently proposed in the United Kingdom from London to Glasgow with several route options through the Midlands, Northwest and Northeast of England and was reported to be under favourable consideration by the government. But the technology was rejected for future planning in the Government White Paper *Delivering a Sustainable Railway* published on 24 July 2007. Another high speed link is being planned between Glasgow and Edinburgh but there is no settled technology for it.

Iran

Iran and a German company have reached an agreement on using maglev trains to link the cities of Tehran and Mashhad. The agreement was signed at the Mashhad International Fair site between Iranian Ministry of Roads and Transportation and the German company. Maglev trains can reduce the 900 km travel time between Tehran and Mashhad to about 2.5 hours. Munich-based Schlegel Consulting Engineers said they had signed the contract with the Iranian ministry of transport and the governor of Mashad. "We have been mandated to lead a German consortium in this project," a spokesman said. "We are in a preparatory phase." The next step will be assemble a consortium, a process that is expected to take place "in the coming months," the spokesman said. The project could be worth between 10 billion and 12 billion euros, the Schlegel spokesman said. Siemens and ThyssenKrupp, the developers of a high-speed maglev train, called the Transrapid, both said they were unaware of the proposal. The Schlegel spokesman said Siemens and ThyssenKrupp were currently "not involved." in the consortium

Japan

Tokyo — Nagoya — Osaka



Proposed Chūō Shinkansen route (thin broken orange line) and existing Tōkaidō Shinkansen route (bold solid orange line).

The plan for the Chūō Shinkansen bullet train system was finalized based on the Law for Construction of Countrywide Shinkansen. The Linear Chuo Shinkansen Project aims to realize this plan using the Superconductive Magnetically Levitated Train, which connects Tokyo and Osaka by way of Nagoya, the capital city of Aichi, in approximately one hour at a speed of 500 km/h. In April 2007, JR Central President Masayuki Matsumoto said that JR Central aims to begin commercial maglev service between Tokyo and Nagoya in the year 2025.

Venezuela

Caracas – La Guaira

A maglev train (TELMAGV) has been proposed to connect the capital city Caracas to the main port town of La Guaira and Simón Bolívar International Airport. No budget has been allocated, pending definition of the route, although a route of between six and nine kilometres has been suggested. The proposal envisages that, initially, a full-sized prototype train would be built with about one kilometre of test track.

In proposing a maglev system, its improved life and performance over mechanical engines were cited as important factors, as well as improving comfort, safety, economics and environmental impact over conventional rail.

China

Shanghai – Hangzhou

China is planning to extend the existing Shanghai Maglev Train, initially by some 35 kilometers to Shanghai Hongqiao Airport and then 200 kilometers to the city of Hangzhou (Shanghai-Hangzhou Maglev Train). If built, this would be the first inter-city maglev rail line in commercial service.

The project has been controversial and repeatedly delayed. In May 2007 the project was suspended by officials due to concerns about radiation from the maglev system. In January and February 2008 hundreds of residents demonstrated in downtown Shanghai against the line being built too close to their homes, citing concerns about sickness due to exposure to the strong magnetic field, noise, pollution and devaluation of property near to the lines. Final approval to build the line was granted on 18 August 2008. Originally scheduled to be ready by Expo 2010, current plans call for construction to start in 2010 for completion by 2014. The Shanghai municipal government has considered multiple options, including building the line underground to allay the public's fear of electromagnetic pollution. This same report states that the final decision has to be approved by the National Development and Reform Commission.

The Shanghai municipal government may also build a factory in Nanhui district to produce low-speed maglev trains for urban use.

India

Mumbai – Delhi

A maglev line project was presented to the Indian railway minister (Lalu Prasad Yadav) by an American company. A line was proposed to serve between the cities of Mumbai and Delhi, the Prime Minister Manmohan Singh said that if the line project is successful the Indian government would build lines between other cities and also between Mumbai centre and Chhatrapati Shivaji International Airport.

The State of Maharashtra has also approved a feasibility study for a Maglev train between Mumbai (the commercial capital of India as well as the State government capital) and Nagpur (the second State capital) about 1000 km away. It plans to connect the regions of Mumbai and Pune with Nagpur via less developed hinterland (via Ahmednagar, Beed, Latur, Nanded and Yavatmal).

United States

Union Pacific Freight Conveyor: Plans are under way by American rail road operator Union Pacific to build a 4.9 mi (8 km) container shuttle between the ports of Los Angeles and Long Beach, with UP's Intermodal Container Transfer Facility. The system would be based on "passive" technology, especially well suited to freight transfer as no power is needed on-board, simply a chassis which glides to its destination. The system is being designed by General Atomics.

California-Nevada Interstate Maglev: High-speed maglev lines between major cities of southern California and Las Vegas are also being studied via the California-Nevada Interstate Maglev Project. This plan was originally supposed to be part of an I-5 or I-15 expansion plan, but the federal government has ruled it must be separated from interstate public work projects.

Since the federal government decision, private groups from Nevada have proposed a line running from Las Vegas to Los Angeles with stops in Primm, Nevada; Baker, California; and points throughout San Bernardino County into Los Angeles. Southern California politicians have not been receptive to these proposals; many are concerned that a high speed rail line out of state would drive out dollars that would be spent in state "on a rail" to Nevada.

Baltimore-Washington D.C. Maglev: A 39.75 mi (64 km) project has been proposed linking Camden Yards in Baltimore and Baltimore-Washington International (BWI) Airport to Union Station in Washington, D.C. It is said to be in demand for the area due to its current traffic/congestion problems.

The Pennsylvania Project: The Pennsylvania High-Speed Maglev Project corridor extends from the Pittsburgh International Airport to Greensburg, with intermediate stops in Downtown Pittsburgh and Monroeville. This initial project will serve a population of approximately 2.4 million people in the Pittsburgh metropolitan area. The Baltimore proposal is competing with the Pittsburgh proposal for a $90 million federal grant. The purpose of the project is to see if the maglev system can function properly in a U.S. city environment.

San Diego-Imperial County airport: In 2006 San Diego commissioned a study for a maglev line to a proposed airport located in Imperial County. SANDAG says that the concept would be an "airports without terminals", allowing passengers to check in at a terminal in San Diego ("satellite terminals") and take the maglev to Imperial airport and board the airplane there as if they went directly through the terminal in the Imperial location. In addition, the maglev would have the potential to carry high priority freight. Further studies have been requested although no funding has yet been agreed.

Atlanta – Chattanooga: The proposed maglev route would run from Hartsfield-Jackson Atlanta International Airport, run through Atlanta, continue to the northern suburbs of Atlanta, and possibly even extend to Chattanooga, Tennessee. If built, the maglev line would rival Atlanta's current subway system, the Metropolitan Atlanta Rapid Transit Authority (MARTA), the rail system of which includes a major branch running from downtown Atlanta to Hartsfield-Jackson airport.

Germany

On 25 September 2007, Bavaria announced it would build the high-speed maglev - rail service from Munich city to its airport. The Bavarian government signed contracts with Deutsche Bahn and Transrapid with Siemens and ThyssenKrupp for the 1.85 billion euro project.

On 27 March 2008, the German Transport minister announced the project had been cancelled due to rising costs associated with constructing the track. A new estimate put the project between 3.2 and 3.4 billion euros.

Indonesia

There are plans to build a 683 km long Maglev rail service between Jakarta and Surabaya. This Maglev will have 7 stations including Semarang. PT Maglev Indonesia working together with SNCF, Transrapid Deutschland, and other corporations will begin this construction around 2010.

Significant incidents

There have been two incidents involving fires. The Japanese test train in Miyazaki, MLU002, was completely consumed in a fire in 1991. As a result of the fire, political opposition in Japan claimed maglev was a waste of public money. On 11 August 2006, a fire broke out on the Shanghai commercial Transrapid, shortly after leaving the terminal in Longyang; nobody was injured. The cause is believed to be a fault with the Maglev's electrical system, it has been suggested to have been an onboard battery unit.

On 22 September 2006, a Transrapid train collided with a maintenance vehicle on a test/publicity run in Lathen (Lower Saxony / north-western Germany). Twenty-three people were killed and ten were injured; these were the first fatalities resulting from an accident on a Maglev system. The accident was caused by human error; charges were brought against three Transrapid employees after a year-long investigation.