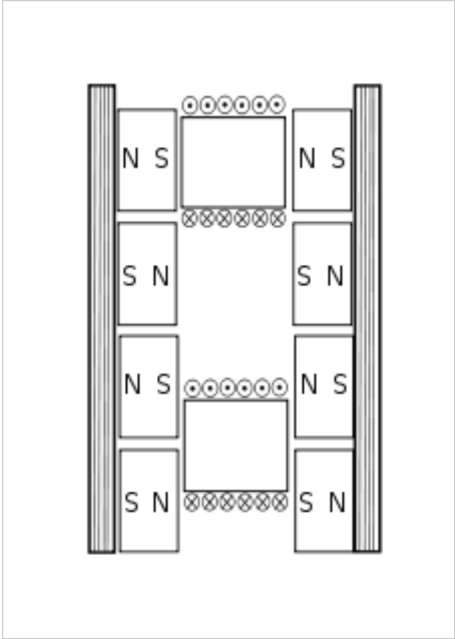
Linear motor

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 $(\vec{F} = q \cdot \vec{v} \times \vec{B})$.



Free-body diagram of a U-channel synchronous 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. (Not to scale)

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 rather short, and are designed to accelerate an object to a very high speed, for example see the railgun.

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 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 Shanghai Transrapid motor is an LSM.

Types


A prototype of linear motor with visible separate coils

Induction motor

In this design, 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 creating motion as the magnetic field sweeps through the metal.

Synchronous motor

In this design the rate of movement of the magnetic field is controlled, usually electronically, to track the motion of the rotor. For cost reasons synchronous linear motors rarely use commutators, so the rotor often contains

permanent magnets, or soft iron. Examples include coilguns and the motors used on some maglev systems, as well as many other linear motors.

Homopolar

A linear motor for trains running Toei Oedo line

In this design a large current is passed through a metal sabot across sliding contacts that are fed from two rails. The magnetic field this generates causes the metal to be projected along the rails.

Piezo electric

Piezoelectric drive is often used to drive small linear motors.

History

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

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,[1] 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.[2] In the late 1940s, professor Eric Laithwaite of Imperial College in London developed the first full-size working model. In a single sided version the magnetic repulsion forces the conductor away from the stator, levitating it, 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.

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.

High acceleration

Close-up of the flat passive conductor surface of a motion control linear motor

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, though RLV launch assist like StarTram to low earth orbit has also been investigated.

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 [3] 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.

Example : Maglev

Usage

Linear motors have been used for sliding doors and various similar actuators.

Linear motors are sometimes used to create rotary motion, for example, they have been used at observatories to deal with the large radius of curvature.

A linear motor has been used for accelerating cars for crash tests.[4]

Train propulsion

Guangzhou Metro L5 vehicle made by

Conventional rails

All applications are in rapid transit.

- 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)

CSR Sifang Locomotive and Rolling Stock and Kawasaki Heavy Industries

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

- 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).[5]
  - 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[6][7]) or a third rail (ART[8]) to transfer power to the train.

Monorail

- 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.

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) [9]
- HSST: Linimo line in Aichi, Japan (opened 2005)

The Birmingham International Maglev shuttle.

Amusement rides

There are many roller coasters throughout the world that use LIM to accelerate the ride vehicles. The first being *Flight of Fear* at Kings Island and Kings Dominion. Both opened in 1996.