Linear Motors
and their modern applications

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Source: Siemens AG

A linear motor is simply one which produces motion in a straight line rather than in a circle. We give an overview of the technology and its applications, including examples of 'genuine' linear motors and related devices.

Although space does not permit a full introduction to electromagnetic theory in this article, we should mention that there are linear drive systems where electricity is turned into motion in a straight line which we nevertheless do not count as genuine 'linear motors'. These are so-called dynamic actuators which operate on a very simple principle using a magnet and a coil, and which have long been used in various applications.

A good example of this type of drive is the classical dynamic loudspeaker. **Figure 1** is a diagram of its construction. Its operation is simple and well known: a coil in a magnetic field experiences a force proportional to the current flowing in it. Apart from applications in sound production, this principle has been in use for almost 20 years in the positioning mechanisms for read/write heads in hard disk drives. Once capacities exceeded 40 Mbyte and track widths shrank, a more precise head drive mechanism was required than the rotary stepper motor design like that used in floppy disk drives. Under control of specially-designed position sensors, the 'voice coil' mechanism, as it is known, achieves previously unattainable tracking precision and, thanks to the high force available, fast seek times. In machine tools actuators are starting to be used for simple and short linear motions, replacing pneumatic systems. In these, the roles of coil and magnet are reversed: the coil is fixed and the magnet or piece of metal moves. In contrast to pseudo-linear actuators, where the linear motion is derived from the rotation of a conventional electric motor using a rack and pinion or a belt drive, these solutions have the advantage of being smaller and simpler.

Further advantages include less wear and tear, high power and consequent ease of use and reliability. Since pseudo-linear motors are cheap to produce and can act over greater distances, they will still have their applications in machine tools.

Genuine linear motors

A genuine linear motor differs from its rotary cousins simply in that the stator (the outer cage within which the rotor turns) is flattened out. The rotor then becomes an object which moves along the stator rails or which encloses the one-dimensional stator. Since the translatory motion in a particular direction is produced without the use of rack and pinion mechanisms or the like, this kind of drive is often simply referred to as 'direct drive'.
Therein lies the chief advantage: with many fewer moving parts there is much less wear and tear and practically no play in the mechanism. This all leads to very high reliability.
It is interesting to note that the principle has been known for over 150 years, although industrial use has only been widespread for the last 30 years or so. This is because the great position sensing precision required for machine tools, in the micrometre range, has only recently become achievable using specially-designed semiconductor sensors and high-speed electronic motor controllers.
The enormous power available (accelerations of 20 *g* and more can realistically be achieved in practice) make linear motors a good choice more generally, where rotational motion is not needed.
In theory all the principles employed in rotary electric motors, including stepper motors and three-phase machines, can be applied to linear motors. And, depending on the application, these motors can be bought off-the-shelf in a range of power output levels, maximum displacements and physical constructions. This includes variants with stationary or moving windings, with permanent magnets or electromagnets, and exotic designs for special applications.

Rail guns and catapults

Few technological advances escape application to destructive ends, and linear electromagnetic drives are no exception. **Figure 2** shows a schematic diagram of a gun-like device which, because of its construction, is known as a 'rail gun'. A conductive projectile slides between two copper rails and experiences acceleration when a current flows. During the second world war Germany tried (without success) to construct weapons using this very straightforward principle. Fortunately such weapons are not widely used even today, because of the extremely high currents (thousands or millions of Amps) involved and the great forces that the components of the weapon must withstand.
Using a electromagnetically-propelled projectile as a large-scale catapult is an area of military research. In principle, a catapult would be an ideal way of launching a high-speed aircraft using a scramjet engine. Scramjet engines only start to operate when a relatively high minimum speed is exceeded, rather more than the speed of sound. Experiments to date using working prototypes use a supplementary rocket engine, or the prototype is piggy-backed on a conventional military aircraft and taken to a great height: it is then allowed to fall until it reaches the required speed for the engine to start. With scramjets capable of a speed of up to Mach 15, it is technically reasonable to use a catapult to accelerate them up to several times the speed of sound and start them. It is at least

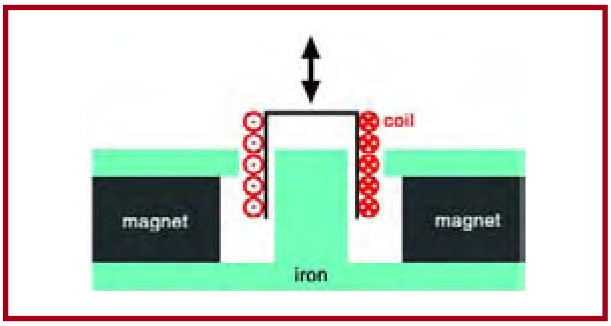

Figure 1.
Principle of the dynamic loudspeaker. This type of drive is used in actuators in industrial applications.

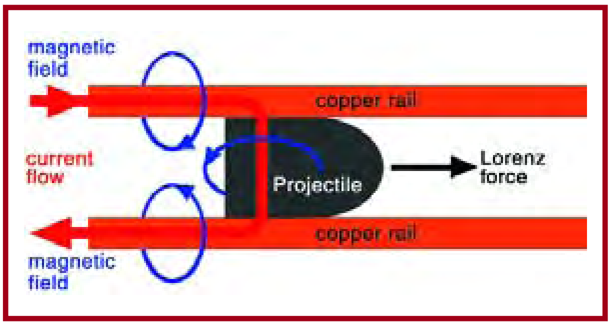

Figure 2.
The 'drive' in a rail gun is very simple. Two current-carrying rails and a conducting projectile are all that is required.

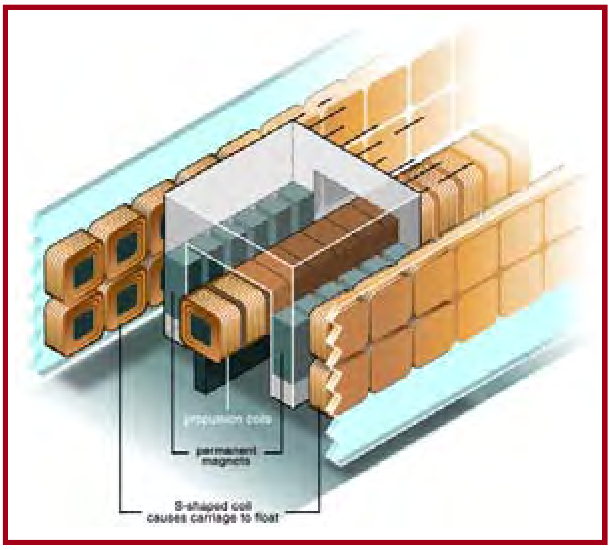

Figure 3.
The linear motor in a catapult. Propulsion and guidance coils allow a metal saddle to be accelerated and keep it on its track. (Source: Schwandt Infographics)

theoretically possible to achieve this using high-powered linear motors (**Figure 3**). NASA has already produced a number of small-scale working research models, sponsored by the military. The system is still, however, science fiction, since the forces cannot be properly controlled, it is extremely expensive and humans are not capable of surviving the necessary accelerations unharmed if the catapult track is short (less than 10 km in length). Practical applications of linear motors to the transport of human beings are taking a different course.

The Transrapid

Relatively high speed trains can be constructed using conventional rotary motors and wheels on rails: the Japanese Shinkansen bullet trains, the German ICE and the French TGV can reach speeds of over 300 km/h. At higher speeds special track must be laid and wear and tear from friction become significant. An experimental version of the TGV in 1990 reached an incredible 515.3 km/h,

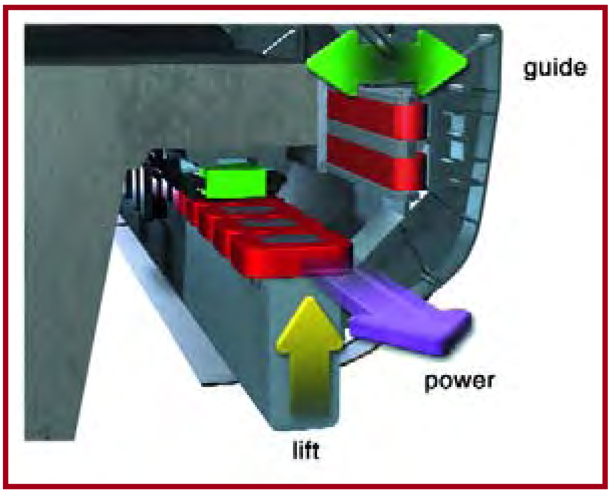

Figure 4. Propulsion and guidance system of the Transrapid train in cut-away view. (Source: Siemens AG)

although at these speeds the overhead wires and pantographs required maintenance after just this one journey. Magnetic levitation railways experience no wear and tear due to friction and it is natural to propel a magnetically-levitated train using a linear motor. Practical versions of this idea are the Japanese JR-Maglev and the German Transrapid. Decades of research have gone into both systems. The Transrapid has been in regular operation in Shanghai for almost two years and has already transported over a million passengers over its 30 km route at some 430 km/h. Both systems are designed for practical use at around 500 km/h and in principle could be run even faster. Consideration is being given to installing a stretch of Transrapid track in the Netherlands (see http://www.magneetzweefbaan.nl/magneetzweefbaan/Default.asp?p=17); in Germany there is still only a prototype track at Emsland in Lower Saxony.

Levitation technology

In the Transrapid design levitation and propulsion are combined. **Figure 4** shows a cross-section of the track and levitation/propulsion system of the train. On the left and right of the track there are metal plates upon which the guidance electromagnets act. The electromagnets responsible for lifting the train act on the laminations which form the flat stator built into the underside of the track on the left and on the right. The air-gap, electronically controlled from within the train itself, is just 10 mm. The windings responsible for propulsion are incorporated into the laminations, made of an isolated aluminium cable with a cross-sectional area of some 300 mm^2. The whole thing functions in the same way as a three-phase synchronous motor laid flat. A travelling magnetic field is induced in the windings in the track. If there is a current in the lifting magnets, they, and hence the train, are lifted up. Since the train envelops the track, it is practically impossible for it to become derailed. **Figure 5** shows a view of the actual construction with the covers removed. Each train or carriage is independently levitated and propelled by the track. There is thus no separate locomotive to pull or push the train. The speed of the train is directly related to the frequency of the alternating currents supplied to the windings, reaching 300 Hz for a speed of approximately 550 km/h in the case of the Transrapid.
It is worth asking how the 10 mm air gap can be maintained at these speeds. The gap is inductively measured thousands of times per second by each segment of the train and the currents in the guidance and levitation electromagnets correspondingly regulated. Taking into account the mass of the carriage a practical control frequency is around 30 Hz. To levitate one segment of the train and guide it around a curve of track requires an electrical power of between 55 kW and 110 kW, depending on load. The necessary energy comes from a suitably-dimensioned battery which is capable of maintaining levitation for approximately one hour if power is lost. If the battery becomes discharged the train lowers itself onto runners. The battery is inductively charged from harmonics of the magnetic propulsion field when the train is travelling at over 100 km/h.
A train composed of three segments requires a drive power of up to 45 MVA at a speed of 500 km/h. So that the whole track is not always powered, it is divided into many short sections selectively driven by inverters placed along the track. The inverters are constructed using power semiconductors such as GTO (gate turn-off) thyristors and IGBTs (insulated gate bipolar transistors) operating at voltages of over 4000 kV and currents of over 1 kA each. The inverter stations control both frequency and voltage and receive commands from a central control station for the track. The Transrapid therefore does not require a driver on the train.
The modern traveller will naturally be concerned as to whether his laptop will operate correctly or whether the data on the magnetic stripe on his credit-card will survive in the neighbourhood of such high-energy magnetic fields. Since the air gap is relatively small at 10 mm the stray magnetic fields are kept to a minimum and the field inside the passenger compartments is comparable in magnitude to the natural magnetic field of the earth. Things are rather different in the case of the Japanese JR-Maglev system where the train rides on a repelling magnetic field. This demands a greater air gap in the region of 10 cm, creating stray fields up to a thousand times greater than those of the Transrapid.
Of course, we have not been able to cover all the details of the systems here. More in-depth information can be found by searching the Internet using keywords such as 'linear motor', 'rail gun', 'scramjet', 'transrapid' and 'maglev'. Wikipedia also has a considerable amount of useful information.

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Figure 5. Under the covers of the propulsion and guidance system of the Transrapid train. (Source: Siemens AG)