Types of Linear motors

The linear motor was invented by Professor Eric **Laithwaite**, the British electrical engineer who died on 6th December 1997, aged 76. It projected a shuttle across a weaving loom using a linear motor. Professor **Laithwaite** had been fascinated with the weaving process ever since his boyhood spent in Lancashire, the UK's home of textile manufacture.

Professor **Laithwaite** described his invention as "no more than an ordinary electric motor, spread out". The principle created magnetic fields on which an object rested and traveled without being slowed by friction. This magnetic levitation had long been understood, but it was Laithwaite who pioneered the commercial development of the first practical applications, developing direct linear drives for both machinery and transport.

Linear motors have evolved in several guises but perhaps the most commonly encountered are tubular types, flat or "U" channel types, which are finding increasing use thanks to their low profiles and high output. For all intents and purposes, and for the purposes of this book, we can assume most linear motors, for motion control, use brushless technology.

The forcer (rotor) is made up of coils of wires encapsulated in epoxy and the track is constructed by placing magnets on steel. The forcer of the motor contains the windings, hall effect board, the rmistor and the electrical connections. In rotary motors, the rotor and stator require rotary bearings, to support the rotor, and maintain the air gap between the moving parts. In the same way linear motors require linear guide rails which will maintain the position of the forcer in the magnetic field of the magnet track. At the same time rotary servo motors have encoders mounted to them, to give positional feedback of the shaft. Linear motors need positional feedback in the linear direction and there are many different linear encoders on the market today. By using a linear encoder, position is directly measured from the load and this again increases the accuracy of the position measurement.

The control for linear motors is identical to rotary motors. Like a brushless rotary motor, the forcer and track have no mechanical connection; i.e., no brushes. Unlike rotary motors, where the rotor spins and the stator is held fixed, a linear motor system can have either the forcer or the magnet track move.

Most applications for linear motors, at least in positioning systems, use a moving forcer and static track, but linear motors can also be used with a moving track and static forcer. With a moving forcer motor, the forcer weight is small compared to load. However, there is the need for a cable management system with high flex cable, since the cable has to follow the moving forcer. With a moving track arrangement, the motor must move the load plus the mass of the magnet track. However, there is the advantage that no cable management system is required.

Similar electromechanical principles apply whether the motor is rotary or linear. The same electromagnetic force that creates torque in a rotary motor also does so in the linear counterpart.

Hence, the linear motor uses the same controls and programmable positioning as a rotary motor. In a rotary motor, torque is measured in Nm (lb-ft) and for the linear motors force in N (lb). Velocity is measured in rev/min for the rotary and m/sec (ft/sec) for linear motors. Duty cycles are measured in the same way for both types of motor.

Looking at the various motor types, we see that a linear motor directly converts electrical energy to linear mechanical force and is directly coupled to the load. There is no compliance or windup, and higher accuracy and unlimited travel are achieved. Today, linear motors typically reach speeds of 5m/sec, with high accelerations of 5g in practice.

Theoretically motors can reach over 20g with 40m/sec velocity; however bearings and required motion parameters de-rate this performance somewhat. There is no wear, no lubrication and therefore minimal or no maintenance cost. Finally, there is higher system bandwidth and stiffness, giving better positional repeatability and accuracy as well as higher speed.

A linear motor can be flat, U-channel, or tubular in shape. The configuration that is most appropriate for a particular application depends on the specifications and operating environment.

Cylindrical Moving Magnet Linear Motors

In these motors, the forcer is cylindrical in construction and moves up and down a cylindrical bar which houses the magnets. These motors were among the first to find commercial applications, but do not exploit all of the space saving characteristics of their flat and U channel counterparts.

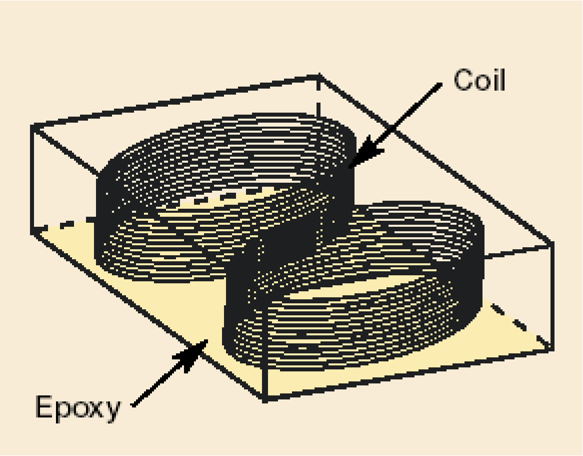
The magnetic circuit of the cylindrical moving magnet linear motor is similar to that of a moving magnet actuator. The difference is that the coils are replicated to increase the stroke. The coil winding typically consists of three phases, with brushless commutation using Hall Effect devices.

The forcer is circular and moves up and down the magnetic rod. This rod is not suitable for applications sensitive to magnetic flux leakage and care must be taken to make sure that fingers do not get trapped between magnetic rod and an attracted surface. A major problem with the design of tubular motors is shown up when the length of travel increases. Due to the fact that the motor is completely circular and travels up and down the rod, the only point of support for this design is at the ends. This means that there will always be a limit to length before the deflection in the bar causes the magnets to contact the forcer.

U Channel Linear Motor

This type of linear motor has two parallel magnet tracks facing each other with the forcer between the plates. The forcer is supported in the magnet track by a bearing system.

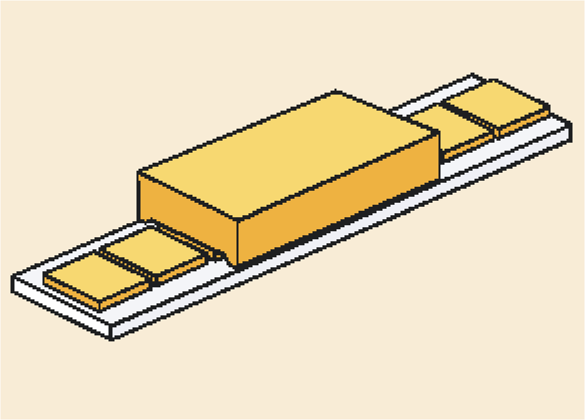
The forcers are ironless, which means that there is no attractive force and no disturbance forces generated between forcer and magnet track. The ironless coil assembly has low mass, allowing for very high acceleration.



Typically, the coil winding is three phase, with brushless commutation.
Increased performance can be achieved by adding air cooling to the motor. This design of linear motor is better suited to reduced magnetic flux leakage, due to the magnets facing each other and been housed in a 'U' shaped channel. This also minimizes the risks of being trapped by powerful magnets.

Due to the design of the magnet track, they can be added together to increase the length of travel, with the only limit to operating length being the length of cable management system, encoder length available and the ability to machine large flat structures.

Flat Type Linear Motors

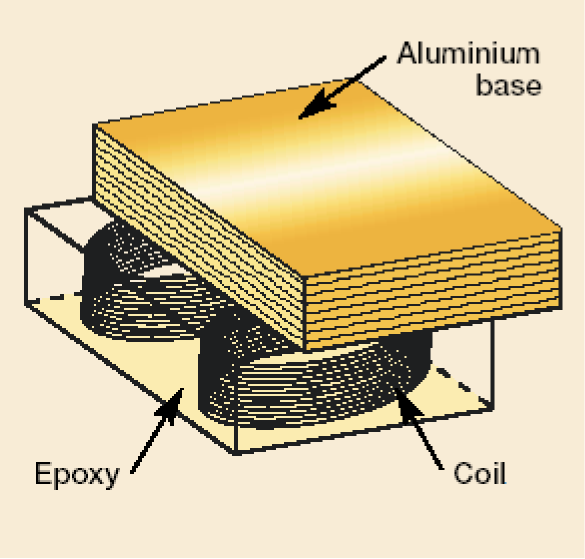


There are three design types of these motors: slotless ironless, slotless iron, and slotted iron. Again, all types are brushless. To choose between these types of motor requires an understanding of the application. The following is a list of the main characteristics of each type of motor.

Slotless Ironless Flat Motors:

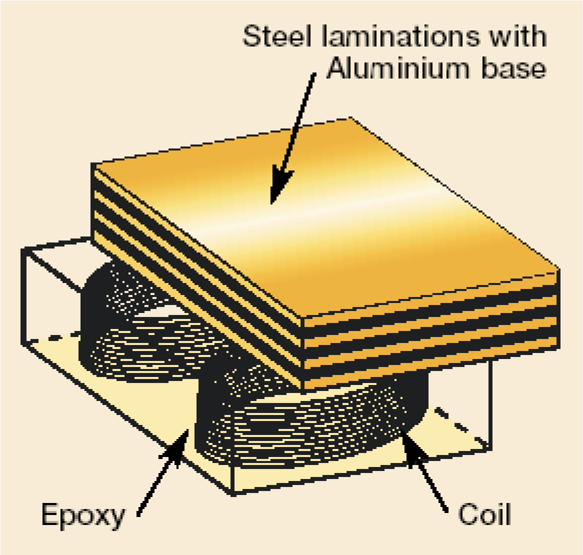
The slotless, ironless flat motor is a series of coils mounted to an aluminum base. Due to the lack of iron in the forcer, the motor has no attractive force or cogging (the same as U-channel motors). This will help with bearing life in certain applications. Forcers can be mounted from the top or sides to suit most applications.

Ideal for smooth velocity control, such as scanning applications, this type of design yields the lowest force output of flat track designs. Generally, flat magnet tracks have high magnetic flux leakage, and as such, care should be taken while handling these to prevent injury from magnets trapping you between them and other attracted materials.



Slotless Iron Flat Motors:

The slotless, iron flat motor is similar in construction to the slotless ironless motor except the coils are mounted to iron laminations and then to the aluminum base. Iron laminations are used to direct the magnet field and increase the force.

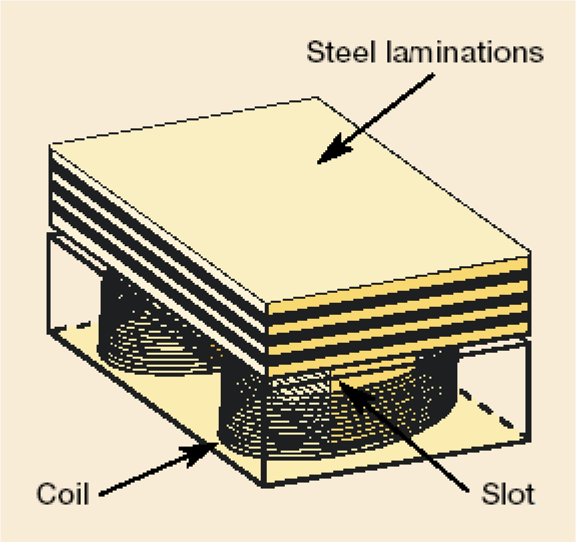


Due to the iron laminations in the forcer, an attractive force is now present between the forcer and the track and is proportional to force produced by the motor. As a result of the laminations, a cogging force is now present on the motor. Care must also be taken when presenting the forcer to the magnet track as they will attract each other and may cause injury. This design of motor produces more force than the ironless designs.

Slotted Iron Flat Motors:

In this type of linear motor, the coil windings are inserted into a steel structure to create the coil assembly. The iron core significantly increases the force output of the motor due to focusing the magnetic field created by the winding. There is a strong attractive force between the iron-core armature and the magnet track, which can be used advantageously as a preload for an air bearing system, however these forces can cause increased bearing wear at the same time. There will also be cogging forces, which can be reduced by skewing the magnets.

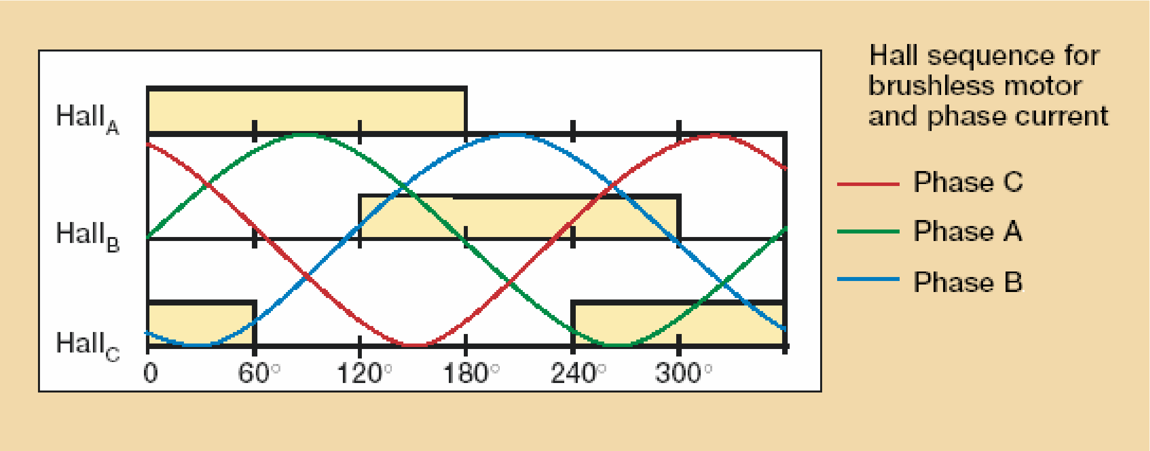
Before the advent of practical and affordable linear motors, all linear movement had to be created from rotary machines by using ball or roller screws or belts and pulleys. For many applications, for instance where high loads are encountered and where the driven axis is in the vertical plane, these methods remain the best solution. However, linear motors offer many distinct advantages over mechanical systems, such as very high and very low speeds, high acceleration, almost zero maintenance (there are no contacting parts) and high accuracy without backlash.



Achieving linear motion with a motor that needs no gears, couplings or pulleys makes sense for many applications, where unnecessary components, that diminish performance and reduce the life of a machine, can be removed.

Commutation of Linear Motors

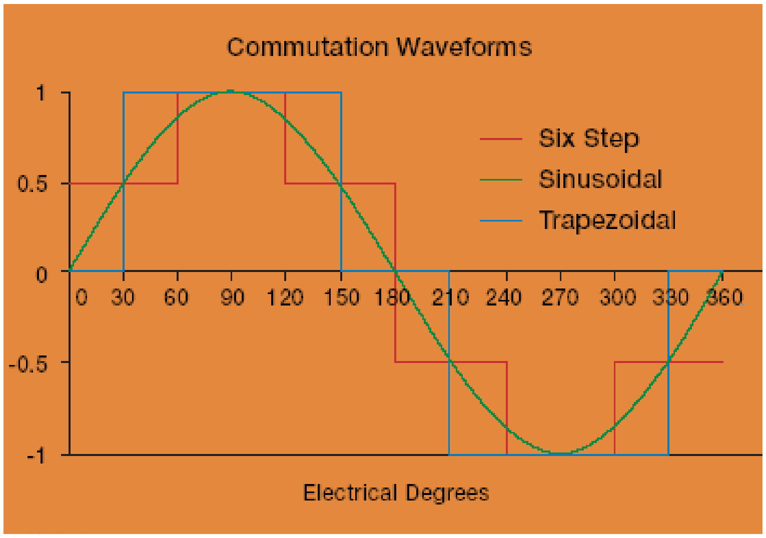
What is commutation and how does it affect the performance of the linear motors? Commutation is the process of switching current in the phases in an order to generate motion. Most linear motor designs today use a 3 phase brushless design. In brushed motors, commutation is easy to understand as brushes contact a commutator and switch the current as the motor moves. Brushless technology has no moving contacting parts and therefore is more reliable. However, the electronics required to control the current in the motor is a little more complex.



Hall sequence for brushless motor and phase current

The method of commutation entirely depends on the application that the motor will be used for, but it is important to understand how the motor can be commutated and what disadvantages some methods have.

To start lets consider the brushed motor. When current is applied to the motor, the correct winding is energized by virtue of the brushes being in contact with the commutator at the point where the winding terminates. As the motor moves, the next coil in the sequence will be excited. In brushless motors because there is no fixed reference, the first thing a control or amplifier must determine is which phase needs to be energized. There are a number of ways that this can be achieved, but by far the most popular is by using Hall Effect devices (Halls). There are three of these devices, one for each phase, and they give a signal that represents the magnetic fields generated by the magnet track. By analyzing these fields, it is possible to determine which part of the magnet track the forcer is in and therefore energize the correct phase sequence.

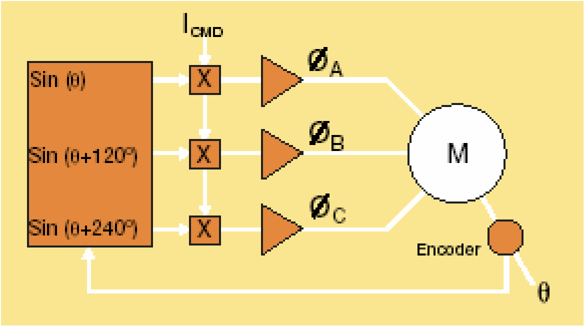


There are three different types of commutation currently available on the market: Trapezoidal, Modified six steps and sinusoidal. Trapezoidal commutation is the simplest form of commutation and requires that digital Hall devices are aligned 30° electrically from the zero crossing point of the phase. At each point that a Hall signal transition takes place, the phase current sequence is changed, thus commutation of the motor occurs. This is the cheapest form of commutation and the motor phase current looks like the diagram shown above.

Modified six step commutation is very similar to trapezoidal commutation. The digital Hall devices are aligned with the zero crossing point of the phase as per diagram showing the Hall sequence of a brushless motor. Again at each point that the Hall signal translation is seen the phase current is switched. However, with this method two current sensors are used and it provides a commutation sequence that is closer to the ideal sinusoidal phase current. This method is slightly more costly than trapezoidal commutation due to sensing 2 current levels. Both of these Hall based methods will cause disturbance forces resulting in higher running temperature and motion which is not smooth.

The ideal means to drive any sinusoidally wound brushless motor is by sinusoidal commutation. There are two ways that this is commonly achieved. Analog hall-effect devices, which generate a sinusoidal signal as the motor passes over the magnetic poles of the magnet track.

The signals, which are correct for motor commutation, are then combined with the demand signal to correctly commutate the motor.



This method is the lower cost of the two methods, but noise can easily be picked up on the hall devices affecting commutation. Another more popular method of sinusoidal commutation is by using the encoder. When a change of state is detected in the digital Hall signal, the incremental encoder signals can then be used to digitally determine where in the commutation cycle the motor is. Commutation is done by generating a sin(_) phase A command signal and a sin(_ +120) phase B command signal and multiplying this by the current command.

This method of commutation gives the best results, due to the same processor being used to control current, velocity and position and yields faster settling time and tighter servo loops. Also the noise on the digital Halls is much easier to filter out creating a more reliable system. When sinusoidal commutation is used with linear motors, the motion is smooth and the motor is driven more efficiently causing less heating.