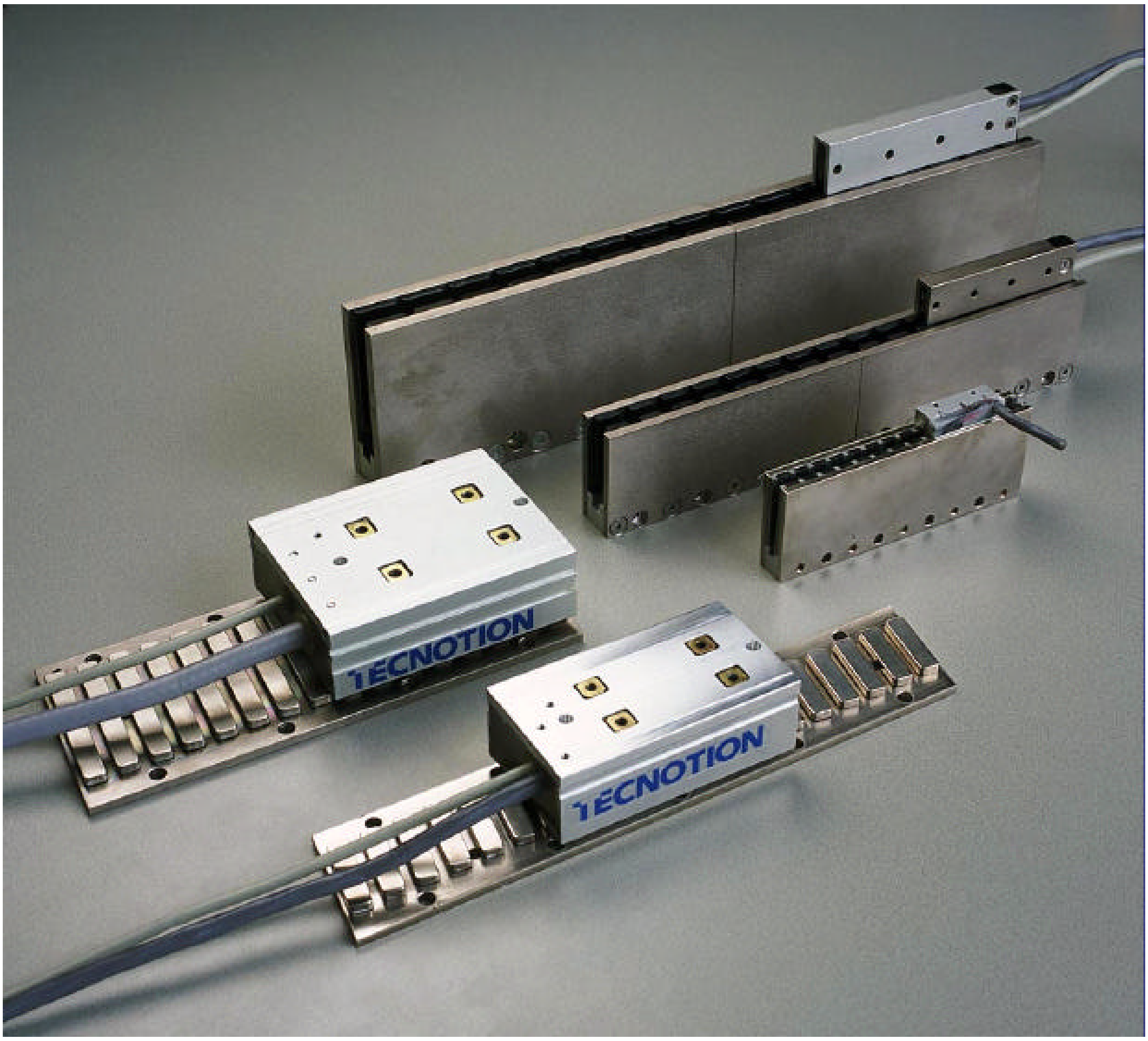
A primer of

LINEAR MOTORS



TECNOTION B.V.
PO Box 23
7600 AA Almelo
The Netherlands

Version 2.0
Document number: 115.773.03.01

Contents:

Introduction

Linear motors (LM) enable linear movements at high speeds with great accuracy. Most linear motors are used in the machine construction industry and for production automation purposes.

In this leaflet the following information can be found:

- The basic physical principles of linear motors.
- The 3 phase linear motor considered.
- A comparison of standard electric (rotary) motors and linear motors.
- The positioning system
- A brief description of a linear motor system and some practical considerations.
- A brief description of both Tecnotion's ironcore and ironless series of linear motors.

This leaflet is the first of a series of four, concerning Tecnotion's Linear Motors. The series consists of the following titles:

- *A Primer of Linear Motors*

- *Designing your Application with Linear Motors*

- *Installing TL and TM series Linear Motors*

- *Installing UM, UL and UC series Linear Motors*

For further information and support, please contact your supplier or

TECNOTION B.V.
LELYWEG 1
PO BOX 23
7600 AA ALMELO
THE NETHERLANDS
TELEPHONE: +31 (0)546 534 666
FAX: +31 (0)546 534 696
EMAIL: SALES@TECNOTION.COM

Basic physical principles

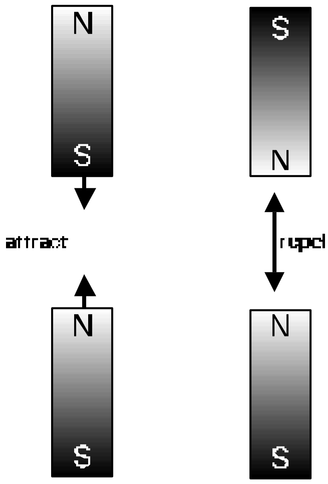


Figure 1: Attraction and repulsion

A very well known physical phenomena is the attraction force between a magnet and iron objects. We also know that a magnet influences another magnet nearby. When two permanent magnets are placed in opposition, they will apply a force to each other. Dependent on the position of the poles, they attract or repel each other. Equal poles are repellent and opposite poles are attracting.

A *linear motor* is propelled by similar magnetic thrusts. Besides permanent magnets here also 'variable magnets' are involved. In these so-called *electromagnets* the variation of the magnetical poles is enabled by using winded cupperwire, i.e. a *coil*, in stead of a permanent magnet.

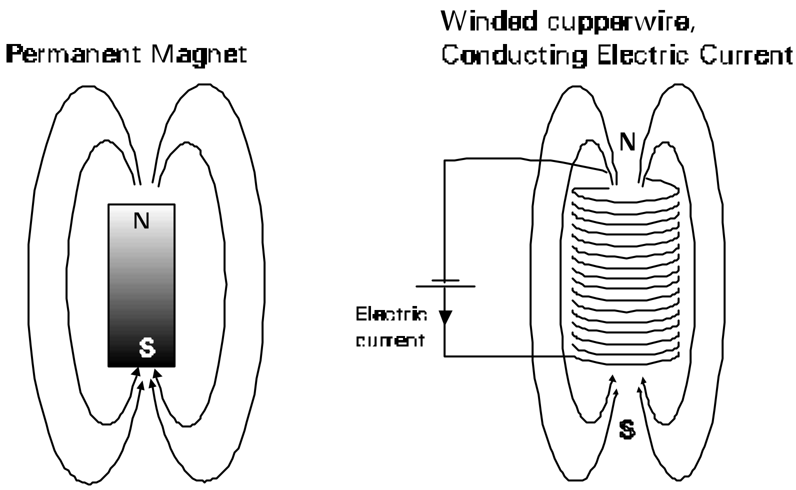


Figure 2: Physical resemblance of permanent magnet and electric coil

It is known that a metal wire, winded around a core and conducting an electric current, acts like a magnet. Among others, the produced magnetic force of an electric coil depends on

1. the amperage of the current,

2. the number of windings, and

3. the kind of core material.

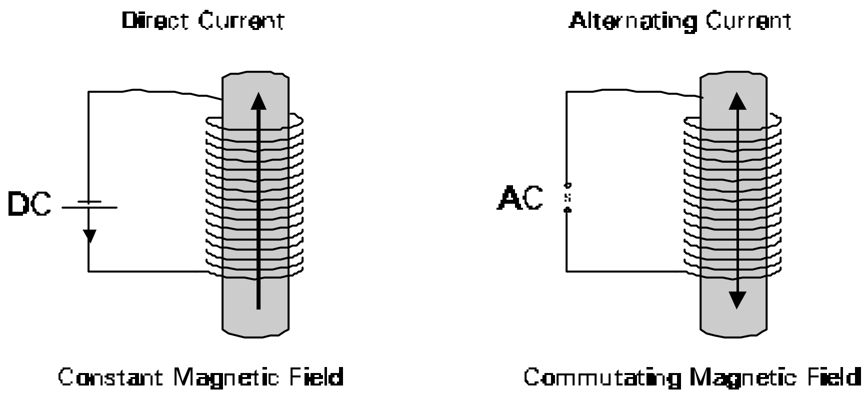


Figure 3: Electromagnetic exiting of a constant and a commutating magnetic field

Generally iron is used as core material. It has some very good characteristics for conducting the magnetic field. In fact the iron core can be considered as a magnet itself. In the case of a direct current the core behaves like a permanent magnet. In addition, reversing the phase of the current makes the magnetic poles switch. So an alternating current excites a commutating magnetic field.

A magnetic circuit

Comparable to electric circuits we can consider *magnetic circuits* as well. Below, an elementary magnetic circuit has been drawn. It consists of an iron yoke, with a permanent magnet and an airgap in it.

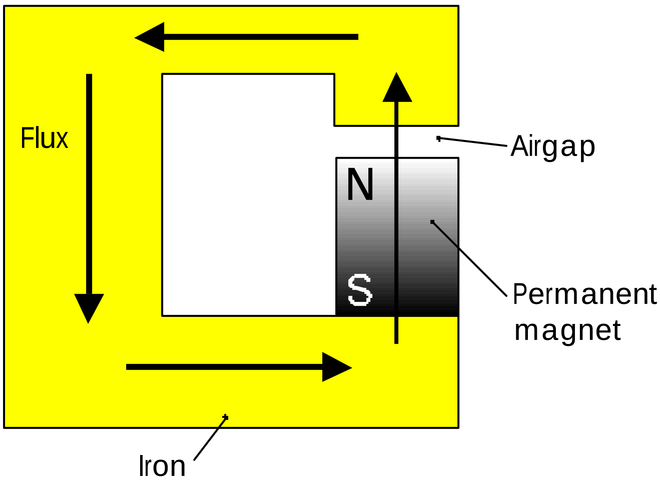


Figure 4: Elementary magnetic circuit

Let's compare this *magnetic circuit* with an *electric circuit.*

- In this comparison, the *magnetic flux* is identical to the *electric current*. The magnetic flux density *B* can be compared to the electric current density *J*.
- A permanent magnet in the circuit can be considered as a fixed *tension-source*, like the voltage-source of an electric circuit. Having a high internal resistance this source drives the flux through the circuit.
- In the considered circuit, the iron of the yoke has a very low resistance and can be used as a *magnetic conductor.* A difference with the standard electric conductor, copper, is that iron shows saturation. This saturation occurs near a certain flux density (about 2.0 Tesla). Above this value, the magnetic resistance of iron increases rapidly.
- Air, copper and non-magnetic materials have a high *magnetic resistance*. Magnetic resistance of a circuit can be determined by the sum of thicknesses of
  - magnets,
  - air, and
  - non-magnetic material

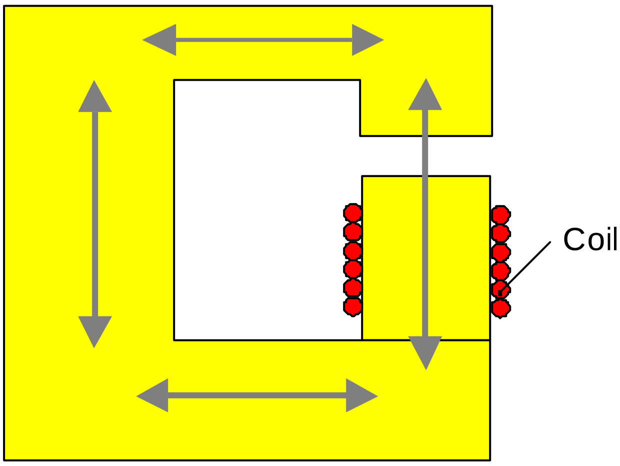


Figure 5: Elementary magnetic circuit

- A coil wound around a magnetic conductor can be considered as a variable tension-source (controlled by coilcurrent), driving the flux through the circuit.
  In this way coils can be used to make adjustable (electro-) magnets which can be switched and controlled by varying the electrical coil current.
- Just like a rolling mass the magnetic flux is subject to some kind of *inertia*. It takes some voltage time to change current and flux, just as a certain time span of force is required to change the velocity of a rolling mass. This effect is known as *selfinductance*.

REMARK:

When a permanent magnet and a coil are combined in a magnetic circuit the counterfield of the coil against the permanent magnet flux can damage (de-magnetize) the permanent magnet. This is not very critical at room-temperature, but the risk increases dramatically at temperatures above 60°C.

The linear motor

Keeping in mind the basic priciples of magnetism as mentioned before, we can consider a simple model of a linear motor.

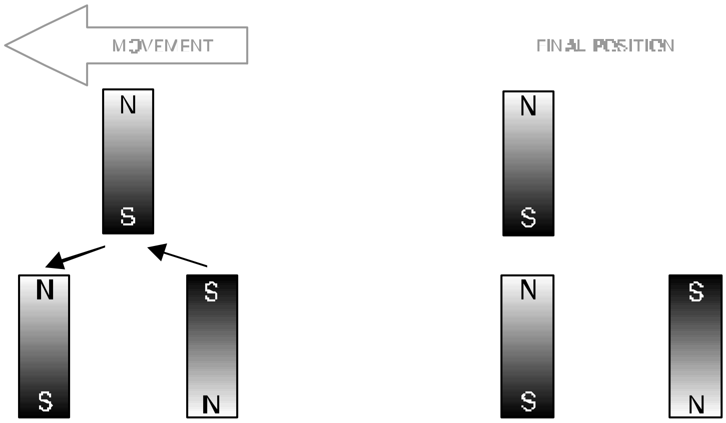


Figure 6: Moving principle 1

Suppose we have a movable but irrotatable magnet which can only be moved in a straight horizontal line. Now this magnet is positioned above two fixed magnets as shown left in figure 6. Because of the attracting and repelling thrusts, it will move towards the magnet with the opposite pole pointing upwards. The movement stops when the magnet is positioned right on top of it.

Now, changing the poles of the upper magnet, would make the magnet move back to the right. This can be obtained by using a coil as upper magnet, see figure 7

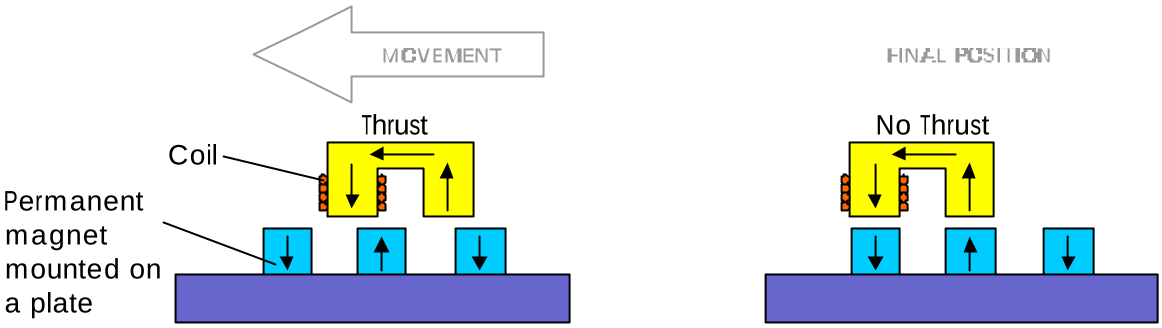


Figure 7: Moving principle 2

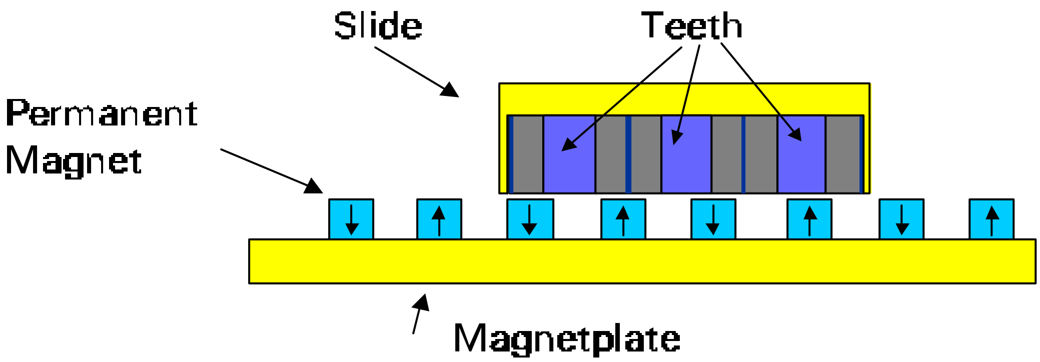


Figure 8: Linear motor, schematic cross section

In a linear motor several coils are mounted in a *slide*, or *coil unit*. The slide is movable over a bottom plate. On the entire distance this plate is covered with permanent magnets. The plate, included with the magnet assembly, is called the *magnetplate*. The length of the magnetplate determines the reach of the linear motor.

One of the two main types of linear motors discussed in this leaflet has coils with an *iron core*. The other main type has an *ironless core*. Each of the types has its specific qualities. The coil poles are often called the '*teeth*' (see figure 9).

The coils are supplied with an electric current. As indicated before the slide is thrusted by changing the current phase of each coil. The speed of change allows control of the velocity of the slide. In addition, the amperage of the current is linked to the moving force. So, in- or decreasing the amperage allows control of the motorforce.

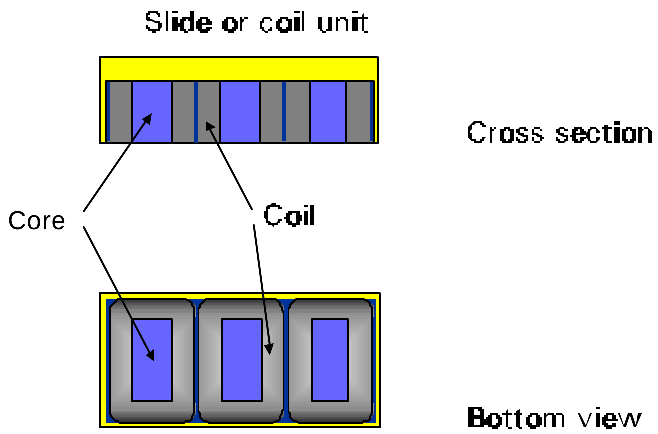


Figure 9: Coil unit with three coils, schematic

3 Phase Linear Motor

Different techniques can be applied in order to get an accurate and smooth motion of the slide. The permanent magnets are fixed on the magnetplate, so the phase of the magnetic force of each magnet is invariable. For the coils on the other hand the phase is adjustable. The slide is propagated by commutating the phase of the current. Providing each coil with a suitable phase displacement is one of the appropriate techniques for linear motors. Another point of concern is the position of the teeth in respect to the permanent magnets.

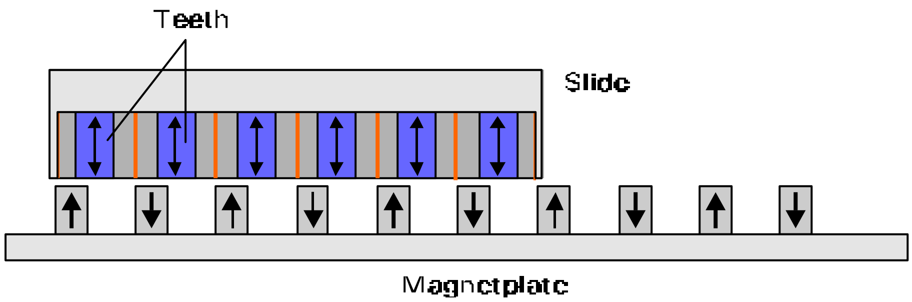


Figure 10: Erroneous postioning and phasing

In order to find out the right way of positioning and phasing let's first consider the obvious wrong way, schematically depicted in figure 10.

- Place the teeth in the same pattern and mutual distance as the permanent magnets.
- In addition, provide the coils with equally phased current.

It won't cost the reader a lot of trouble to find out that the slide won't move at all under these conditions.

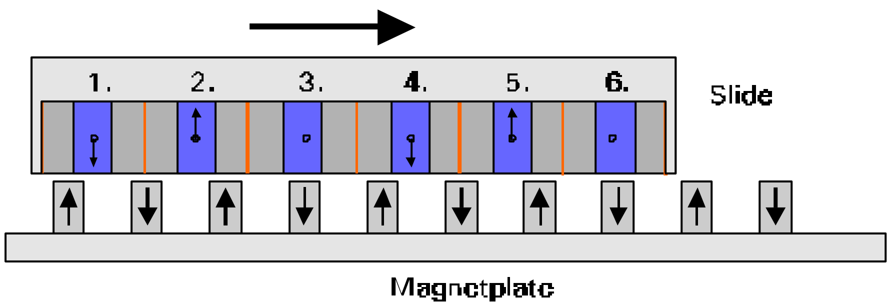


Figure 11: Postioning and phasing for a 3 phase linear motor

The principle of the *three phase linear motor* comes to meet the demands of right positioning and phasing. In figure 11 the teeth are equally positioned in the slide *with a ratio 3 to 4* compared to the magnets of the magnetplate. As a result *three different groups of teeth* can be distinguished. Tooth 1 will continuously have a comparable position as tooth 4. Tooth 2 and 5 are also comparably positioned as well as tooth 3 and 6. Smooth and accurate motion is now obtained by providing a *three phase rotary current* to the coils, one phase to each group. The phase angle depends on the position of the slide.

More in detail, three stages of the motor's motion can be represented as follows:

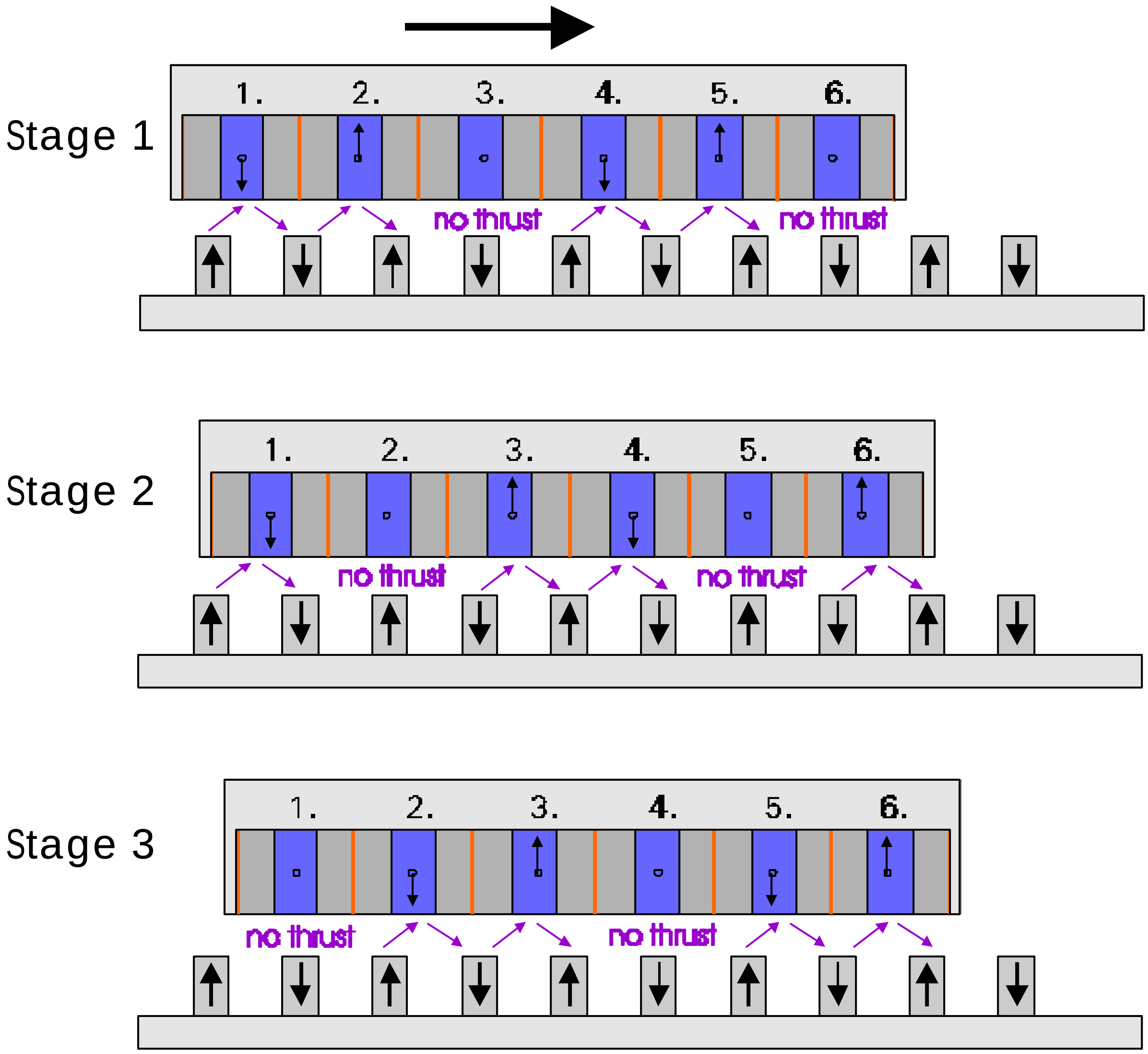


Figure 12: Stages of the 3 phase linear motor's motion

In the first stage the teethgroups 1/4 (north) and 2/5 (south) are active in generating thrust. After a move to the right, teethgroup 2/5 cannot contribute anymore. The phase has to be changed to null. Now, at stage 2, teethgroups 1/4 (north) and 3/6 (phase changed to south) generate the thrust. According to this hand-over-hand scheme the motor can travel over longer distances, depending on the length of the magnetplate.

The required *current* through the coils is a *rotary current*. Usually this is represented as a clock- or counterclockwise running arrow in a XY-graphic.

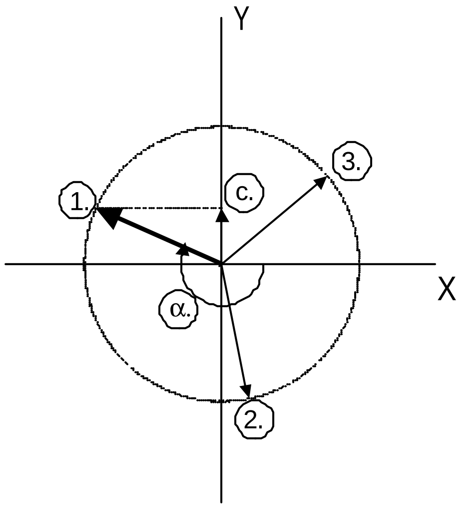


Figure 13: Graphical representation of the coil's current.

In figure 13 arrow 1 is related to the current in coilgroup 1/4. As the *commutation angle a* changes, the position of arrow 1 alters, as well as its projection on the Y-axis. This projection (c) depicts the magnitude and the direction of the current, from which can be derived that the current is related to *the sine of the angle a*.

Arrow 2 and 3 are succesively related to coilgroups 2/5 and 3/6. The differential commutation angle between two successive coils is *fixed*. It differs 120°. So the the different coilgroups are *synchronously* powered.

An extended outline of this representation is given in table 1.

As you can see here the differential commutation angle between two successive stages as depicted in figure 12 is -60°. In this difference *the coil's current is related to its position on the magnetplate*. So it is necessary to know the relative position of the coils with respect to the permanent magnets in order to obtain the required thrust. Therefore a linear motor must be *magnetically aligned*.

There are three methods to obtain this information at startup:

1. Is to use an absolute position encoder.

2. Measure the magnetic field with Hall-sensors fixed with the coils.

3. Determine the position by exiting the coils with testcurrents and measure the motors reaction '*wake-and-shake*'. This requires the motor to move freely.

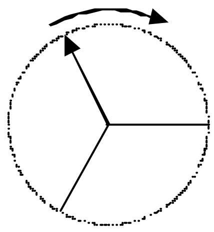
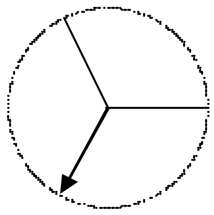
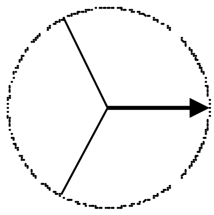
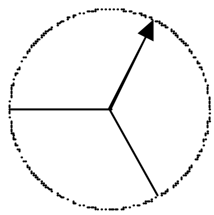
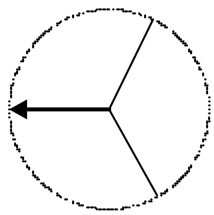
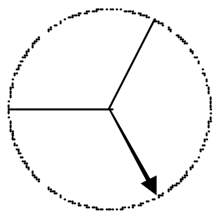
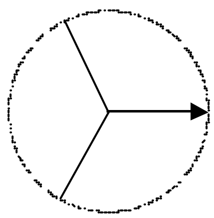
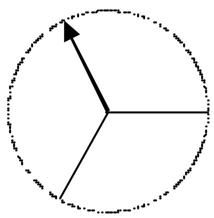
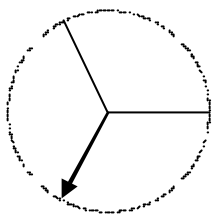
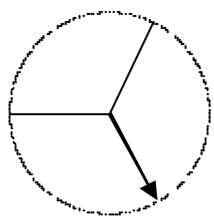
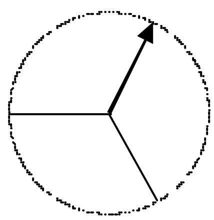
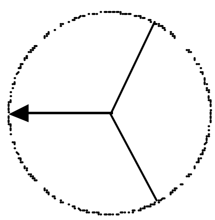
Stage	Phase 1 (current coils 1 & 4)	Phase 2 (current coils 2 & 5)	Phase 3 (current coils 3 & 6)
1			
2			
3			
4			
etc	etc	etc	etc

Table 1: Phase of the coil's current at different stages of the motion

Final remark:

- It will be clear that the coil unit of a 3 phase linear motor houses a *threefold of coils*. One of the distinctions between the various types of motors concerns the amount of triple coils.

Ironcore linear motor

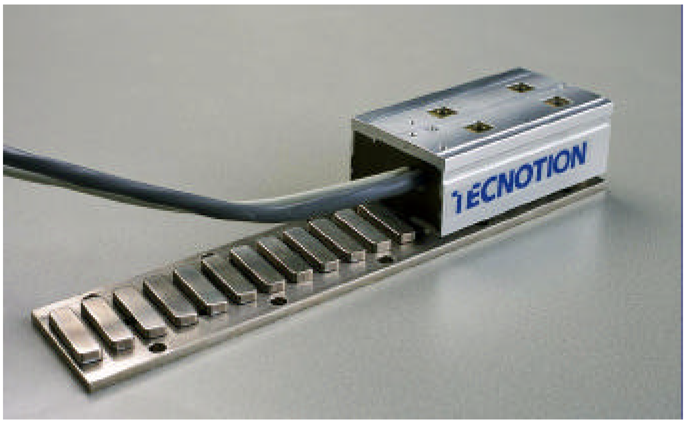


Figure 14: Ironcore coil unit with magnetplate, example TM3

This type of motor has a *low magnetic resistance*. The ironcore and the magnet closing plate are excellent flux conductors, so only the magnets and a single airgap contribute to the resistance in the circuit.

Due to this low resistance the ironcore motor's operation invloves a *strong flux*, yielding *high forces* and an *excellent efficiency*. That makes this type a real workhorse with the following main features:

- high peak force density,
- high continuous force density, and
- relatively low heat dissipation.

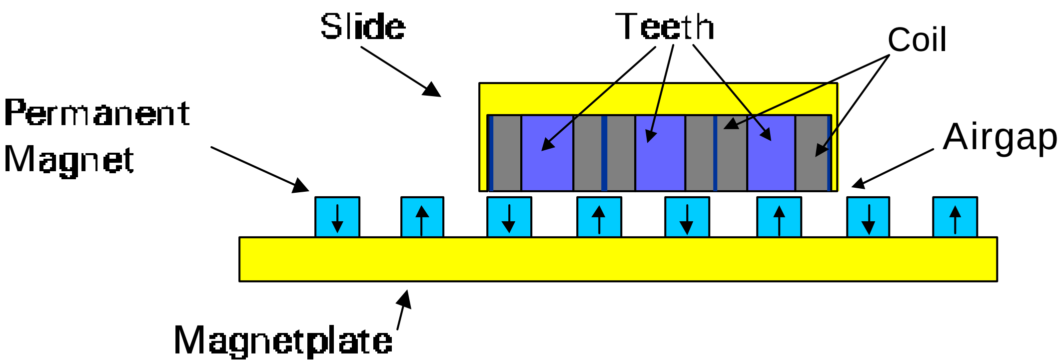


Figure 15: Ironcore linear motor, schematic cross section

This motor type shows however *attraction force* of roughly twice to triple the maximum thrust force. This attractionforce has to be withstand, for instance by bearings, while maintaining the correct airgap between coilunit and magnetplate.

A second effect of the ironcore is *cogging*. Unless careful balancing, the ironcore has always prefered positions with respect to the magnets. Moving the ironcore along the magnettrack, gives a slight feeling of moving over an oldfashioned washingboard. Actually cogging is no problem for most of the applications because it can entirely compensated by a sophisticated feedback loop.

Because of the high flux, the motor has a *considerable induction*. This is convenient for smoothing the current and allowing an economic amplifier, but it requires appropriate voltage for very sudden force changes.

With this type of linear motor there can be reached speeds of up to 10 m/s.

Ironless linear motor

Figure 16: Ironless linear motor, example UL

In stead of a magnetplate the ironless motor is applied with a magnetyoke, comparable with a sandwich of two magnetplates. The ironless coil unit moves freely through the yoke's groove.

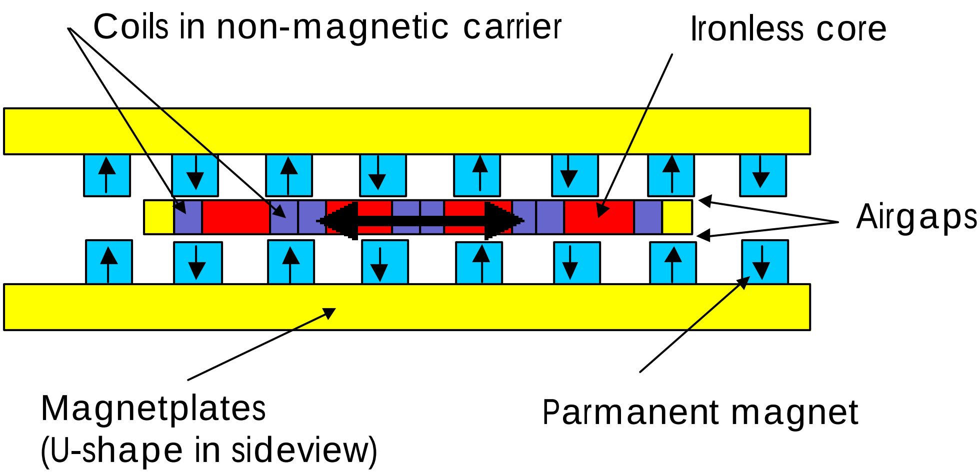


Figure 17: Ironless linear motor, schematic cross section

In comparison with the just described ironcore motor the characteristics of the *ironless type* is mainly influenced by the dissimilar magnetical resistance. In this type the resistance is formed by the magnet heigth, two airgaps plus the coil's thickness. This results in a relative *high magnetic resistance* causing a *low magnetic flux*. Therefore this type is characterized by

- a moderate peak force density,
- a low continuous force density, and

- more heat dissipation compared to the ironcore.Especially the continuous force of such a motor is much lower than that of an ironcore. First by the higher heat dissipation, second by the worse heat conduction to ambient.

On the other hand, because the design is balanced and the coil section contains no magnetic material, the motor has no attraction force at all, and there is absolutely no cogging. The only force generated is the thrust force.

Because of the high magnetic resistance, *the coil's inductivity is relatively low* allowing high rates of change for very quick movements and very quick reactions to disturbance forces. These characteristics make that this motor is very dynamic, and achieves very short settlingtimes and high speeds. Due to this ability of quick changes, the motor requires also a quick and accurate controller and amplifier for obtaining accurate control.

A disadvantage of this type is that the sandwich requires a double row of magnets making the magnetyokes rather expensive compared to the ironcore types.

Linear and rotary motors compared

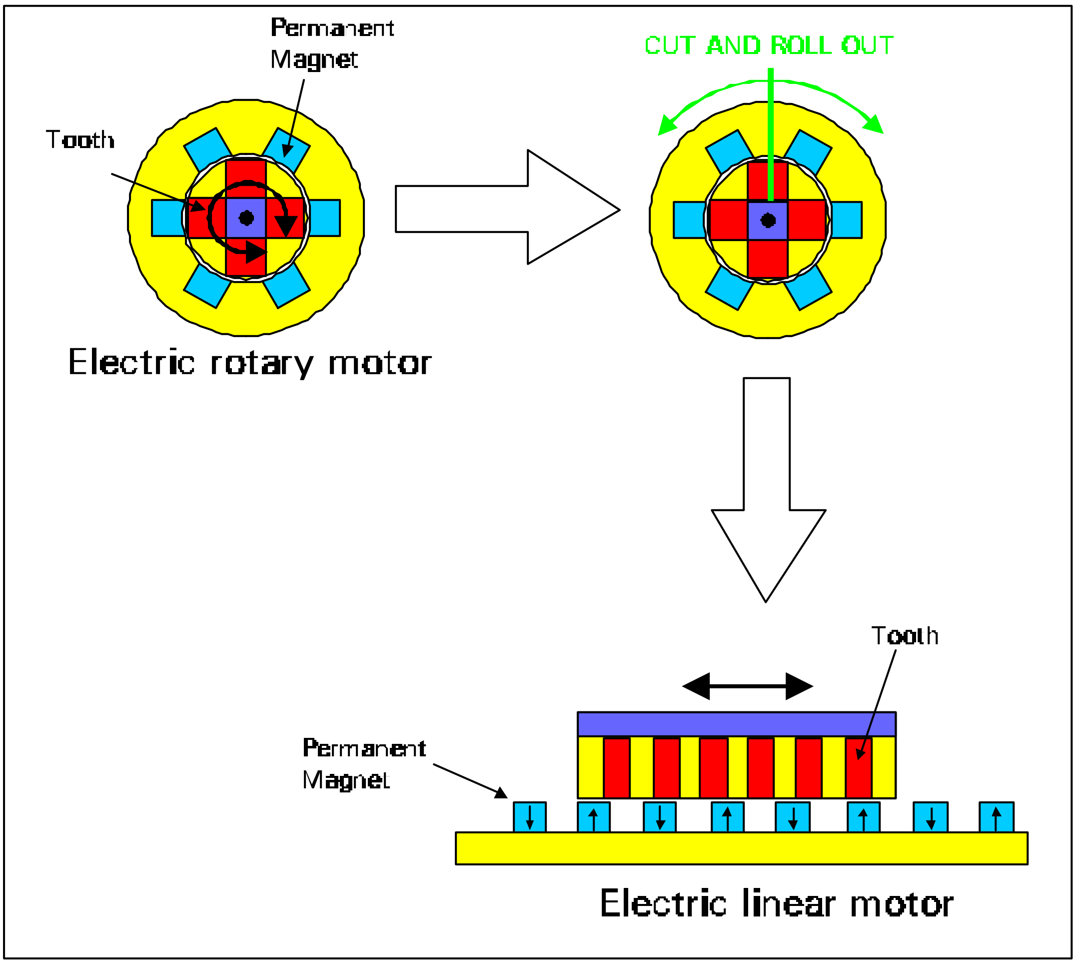


Figure 18: A rotary motor opened up and laid out flat

It will be notified that a linear motor is based on the same physical principles as the normal rotary electric motor[1]. In fact a linear motor is a rotary motor opened up and laid out flat (see figure 18). Hereby the rotor is transformed into the magnettrack. The torque has become a linear force and so the rotary movement has changed to a flat movement.

Because of its flat topolgy the main advantage of the linear motor is apparent. It generates a *direct linear movement*. Whereas a rotary motor needs some kind of transmission to provide a linear motion, the linear motor directly provides it.

1. Meant here is an electric motor with a wired rotor and a sliding contact, whereas the stator consists of permanent magnets.

The *direct drive* results in some significant advantages.

- Accurate position control and response is possible at submicron level.
- A linear motor provides a smooth and controlled motion. No velocity ripple.
- In comparison with standard rotary motor systems a high velocity and acceleration performance is obtained. This is due to the high ratio of peak force to motor inertia.
- Except for the side bearings there is no contacting surface. Friction is negligable, virtually no wear.
- The only limitation on travel displacements is the length of the magnettrack. Since the track can be extended with more magnetplates this limitation mostly is virtual. In the case of added length there are no speed limitations nor is there a higher inertia or lower dynamic stiffness.

The positioning system

Linear motor applications require a sophisticated position and velocity feedback. A linear encoder and a servocontroller are taken up in the positioning system. The position of the slide is detected by a ruler-probe combination. The linear encoder returns this information to the servocontroller.

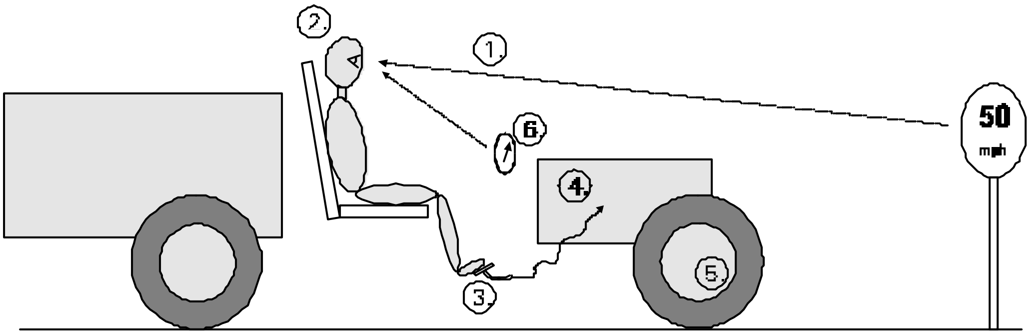


Figure 19: Feedback, delay-time and accuracy

To have some impression of the positioning system a superficial comparison could be made with the speed control of an automobile. The information of the traffic sign (1) is detected and interpreted by the driver (2) and translated into an adjustment of the gaspedal (3). This results in an adjustment of the motor force (4) and consequently of the rotation speed of the wheels (5). The actual speed information is returned to the driver by the speedometer (6). As long as the desired speed is not gained this specific loop back situation is maintained.

What a linear motor system concerns the measurement unit could be compared with the driver’s visual system. The measurement probe detects the position and the linear encoder translates it into the right position information. The imput ports of the servo-controller act like the eye-nerves. Here the position information is returned to the drivers brains, the very servo-controller. In the controller this information is processed and translated into an appropriate voltage signal to the linear motor, comparable with the gas pedal movement. Because the linear motor needs a powerful input this signal is provided by an amplifier. A bigger amplifier supplies a larger peak force, just like a more powerful car engine produces more horse powers. Comparable with car dynamics the acceleration of a linear motor depends on the ratio of the amplifier power and the total moving load. It should be notified that the voltage signal to the linear motor is provided in the form of pulses with a fixed switching frequency and a fixed voltage. So the pulse width is the parameter to be regulated.

The position information provided by the probe is incremental. So the linear motor has to do without the absolute position of the slide. Especially when starting a motor operation this could be problematical. Herefore the slide is activated to some minimal testmovement. This earlier mentioned ‘magnetic alignment’ supplies the positioning system with the required information.

Linear motor system

Overview

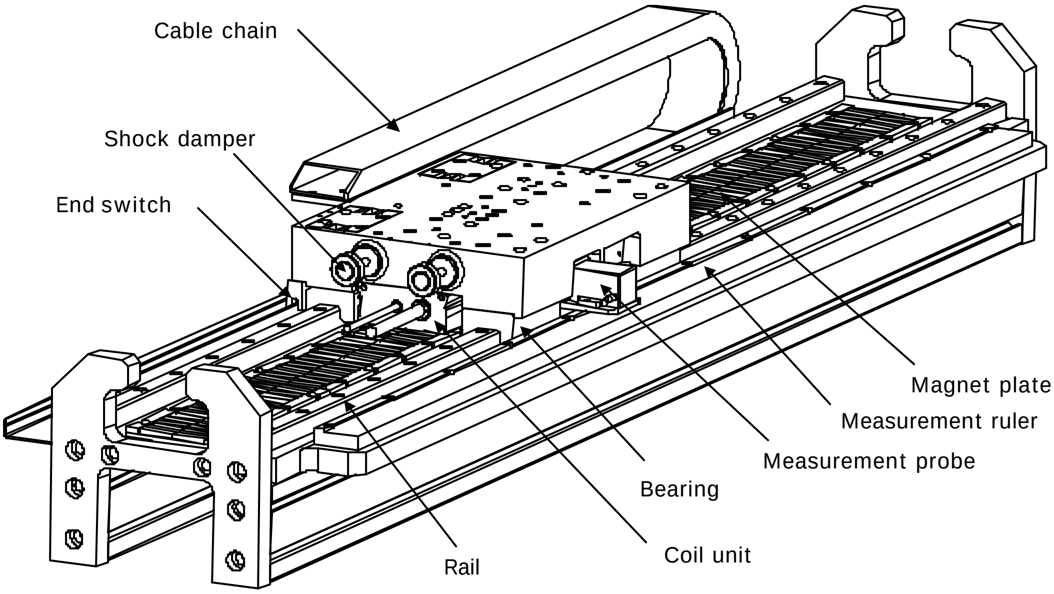


Figure 20: Ironcore linear motor system, example

A linear motor usually is part of a bigger system. This system enables controlled movement. A complete *linear motor system* consists at least of the following parts:

- A mounting frame
- A magnettrack build up out of at least two magnetplates.
- A set of linear guides that support the slide and its load.
- A positioning system consisting of a servo controller, a measurement ruler and probe for position detection and a linear encoder for position feedback to the servo controller.
- A coil unit, water cooled if needed. This slide carries the functional load.
- Safety end dampers and switches to stop the movement in case of malfuntions.

In the next paragraph some practical considerations concerning these items will be discussed.

Document number: 115.773.03.01
Issue date: november 2002

Practical considerations

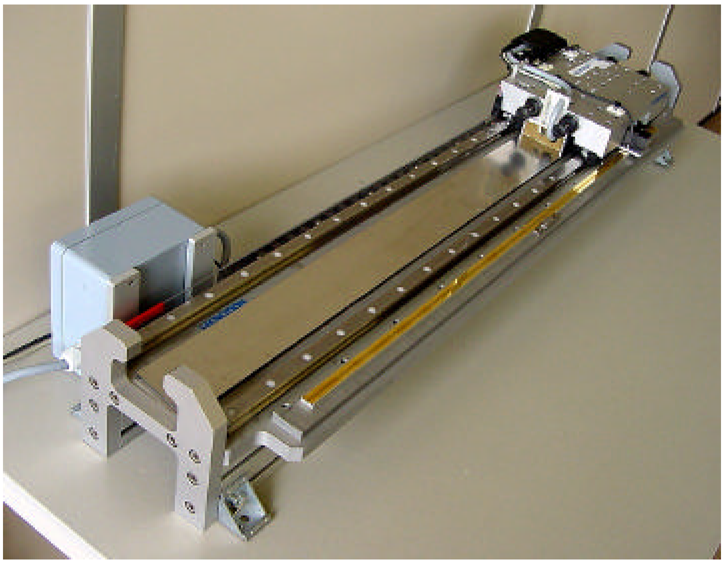


Figure 21: Ironcore linear motor system

A PART OF A TOTAL MACHINE CONCEPT

A linear motor of Tecnotion is not a system on itsself. It should be build within a total machine concept or a working unit. Depending on the application a choice has to be made between different systems. Therefore it is important to know the specifications of both the total machine concept and the linear motor types. The machine should meet all the appilcable CE requirements.

MOUNTING FRAME: SOLIDITY AND STABILITY

For two main reasons the mounting frame has to meet special requirements. The propelling peak forces of a linear motor are high, so the frame needs sufficient dynamic stiffness. Because of the accuracy the frame should be insensible to shocks and vibrations. Usually the magnetplate is horizontally fixed to the base of a machine or working unit. The slide will bear a functional load, such as a measurement unit or a laser cutter. Because of this load, the cabling and optional cooling lines the ratio of peak force to motor inertia could be influenced a little. It will be obvious that a vertical position of a linear motor system demands special considerations. If desired contact Tecnotion.

RAILS AND BEARINGS

To assure a free movement of an ironcore motor the slide has to be provided with bearings that run smoothly on two rails, or with air bearings. The rails are mounted aside the magnetplate. In addition this construction ensures the right

airgap between the coil unit and the magnet plate.
For the sideward positioning of the coil unit to the magnetplates a small tolerance is acceptable.
When using Ironless linear motors, there is much more freedom in the construction then when using ironcore because the ironless motors show no attraction force. Many applications can do with one single ball-bearing rail. As long as mechanical contact is prevented the position of this bearing relative to the motor axis is indifferent. More important is the position of the motor with respect to the center of mass. A large distance can cause rotational oscillations.

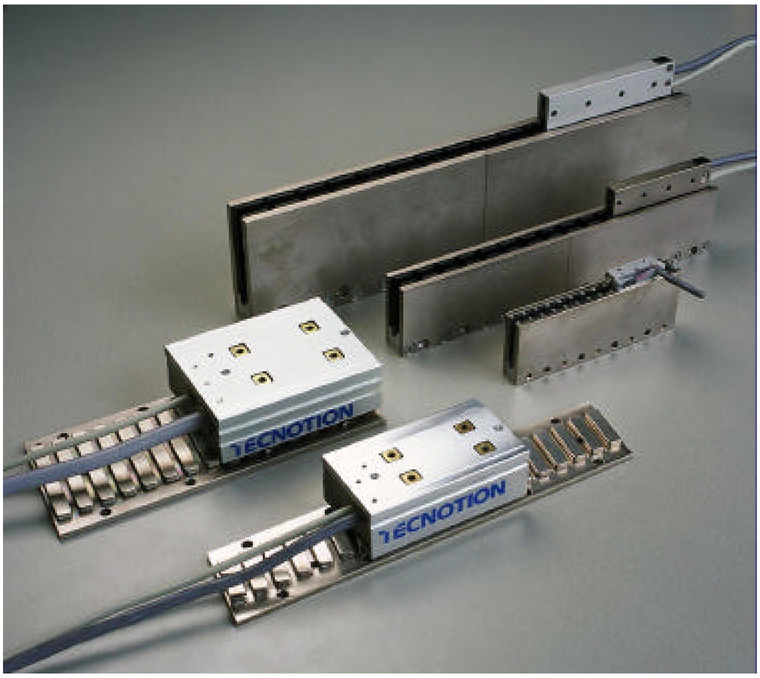


Figure 22: Several types of linear motors

HEAT DISSIPATION

Heat dissipation is a very important issue both for ironcore and ironless motors. Important but difficult as well.

Every linear motor produces heat. There are some aspects to consider:

- The heat is particulary produced in the coils. It spreads through the coils to the aluminium frame and from the coilunit surface to the sled, the air and - partly - to the magnettrack.
- Heatflow causes temperature differences. The heat has to flow as easily as possible to ambient, in order to keep oprational temperature low. If possible, the route of the heat conduction should be traced.
- Temperature differences might lead to expansion of materials. This can be unacceptable for accuracy or other reasons. Sometimes, without cooling an unacceptable heat up of the coil unit could occur. This could result in lower performance, thermic safety stops and even damage to your motor

system. High temperatures might also disturb electronics. The allowed temperature increase for your application, especially for the coil unit, should be determined.

Generally, the heatflow can be optimised by the following measures.

- By using a heatsink compound when mounting the coilunit,
- by directing ventilation in the airgap between the magnets,
- by applying air- or watercooling channels in the mounting surface of the coilunit.

All coil units are fitted with a *temperature sensor*.

ACCURACY

The accuracy of the positioningsystem is crucial, since the linear motor is supposed to be controlled at submicron level. For instance the accuracy can be influenced by heat expansion of the coil unit, by vibrations and shocks from the surroundings or by a lack of stiffness of the mounting frame. Generally the main restriction for the accuracy arises from this lack of stability.

Like most mechanical systems a linear motor deals with mechanical resistance, elasticity and inertia. Because of the feedback of position and velocity it also deals with measuring accuracy and certain delay times. For instance the controller has to deal with some delay because of processor and update times. Accuracy could also be limited by the fixed pulse frequency of the servo-amplifier.

Of course the linear ruler and the measurement probe should meet the desired accuracy. This requires a sophisticated ruler-probe combination. The probe should be mounted as close as possible to the working point of the complete moving unit (slide + load). The probe sends signals to the linear encoder, whereby the encoder has a resolution time.

At last the linear motor itsself is an electromagnetic device. It deals with resistance and selfinductance. This implies that the current in the coils always lags behind the provided voltagesignal. Since the magnetic force is directly linked to the current this means that the motorforce also lags behind. Applying a servo controller with a sophisticated current regulator could minimize this lag-effect.

All these items affect the accuracy of the linear motor, its small signal behaviour.

SERVOCONTROLLER

Tecnotion linear motors can be combined with most common types of 3 phase AC servocontrollers, provided that

- the servocontroller can co-operate with a high resolution linear encoder,
- the servorcontroller can perform the magnetic alignment at startup.

Braking and damping

High velocities are gained at short distances. In normal conditions dynamic braking is provided by a reversed electromagnetic force. However, for short runouts braking and damping could be necessary. In certain conditions, for instance a loss of electrical power, this could be critical for safety.

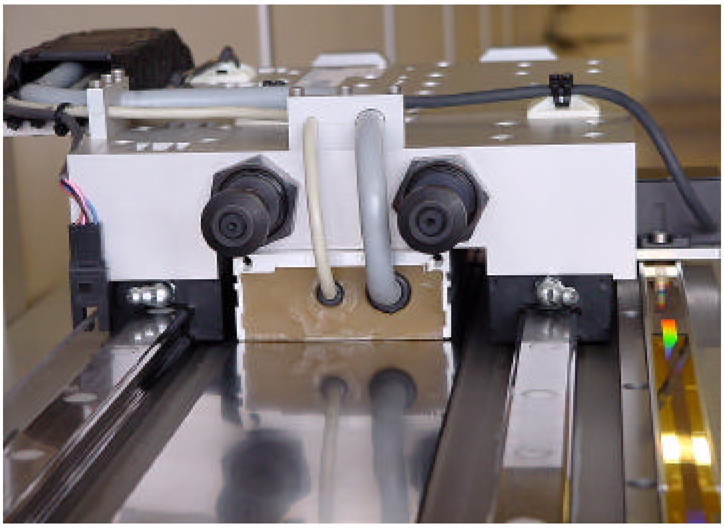


Figure 23: Ironcore motor, seldge, bearings and ruler, detail

Magnetic flux and distance

Just like a rotary motor a linear motor is propagated by an electro-magnetical force. Magnets produce a so called magnetic flux, which can be considered as the density of the magnetic field. This counts for the permanent magnet as well as the electromagnetic coil. The magnetic field is densest in the direct vicinity of the magnetic pole, typically several thousand Gauss. This flux usually diminishes rapidly when measured at some centimeters from the magnet pole. Since the magnetic force depends directly on the magnetic flux, it is important to keep the gap between coil unit and magnetplate small. The gap can vary a little without loosing much performance.

Cogging

The permanent magnets produce an attraction force to all magnetic materials in the vicinty. When the coil unit contains such materials, f.i. the iron core, the motorforce could be influenced. Because of the separate positioning of the magnets on the magnetplate, the magnetic field is not homogenous. So, dependent of the position of the magnets the motorforce will be disturbed. Such position dependent disturbance could make the slide cog. Tecnotions sophisticated design meets with the problems of cogging.

CAREFUL INSTALLATION

Installing a linear motor should be done very cautious. Read the installation manual carefully. Installation only by qualified personal. Special attention should be given to the strong magnetic field in the vicinity of the magnetplates. These plates should be handled with care and with proper tools. Beware of the fact that materials or clothes get jammed between magnetplate and iron objects. For mounting and dismounting purposes magnetic field neutralizing protectionplates are to be used.

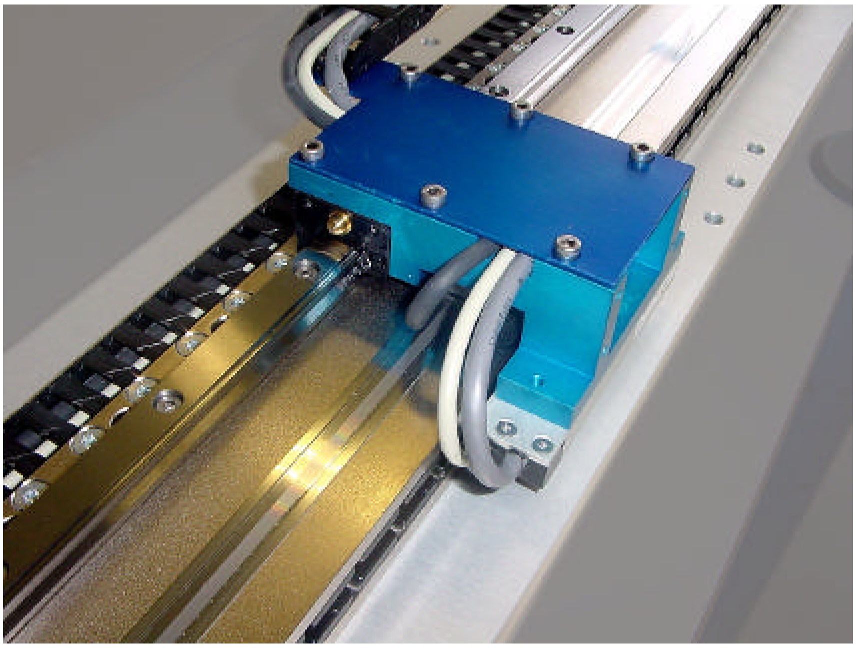


Figure 24: Ironless linear motor system (UL3)

Carefully follow the installation instructions of the applied servo controller ans linear encoder. Electronic wiring, such as the sensor cable, should be shielded or combined to twisted pairs in order to reduce the influence of EMI.

Tecnotion ironcore: the TL and TM series

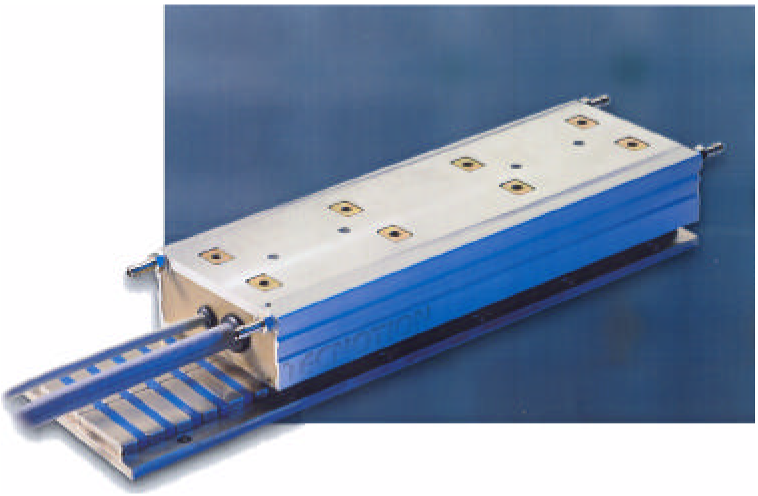


Figure 25: TL12, ironcore, 3 phase, synchronous

The motors of the TL series are three phase ironcore motors in a very compact design. Coils with ironcore are mounted in the slide. The slide moves over the magnetplate. The small gap between the plate and the slide is established by the use of rails and bearings. As stated before this small airgap provides a low magnetic resistance between coils and magnets. This results in a high magnetic force.

Some characteristics of this linear motor type are:

- High peak force (up to 2000 N).
- High continuous force.
- Relatively small attraction force
- Low heat dissipation.
- Controlled low cogging level.
- Dynamics and accuracy at an intermediate level.
- Medium speed (up to 10 m/s).
- Moderate price of magnet plate.

Tecnotion ironless: the UM, UL and UC series

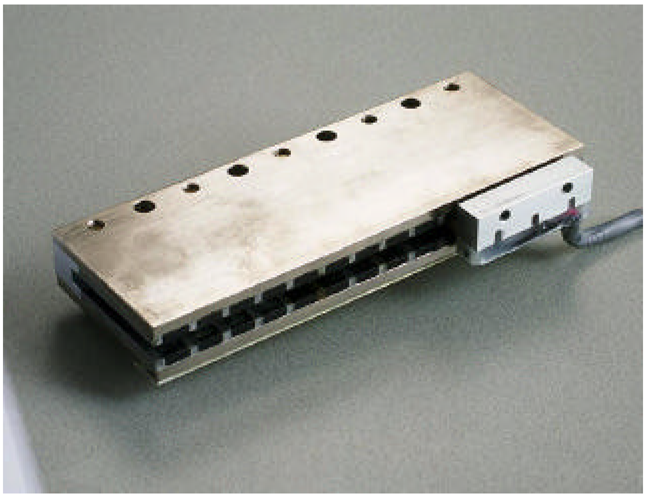


Figure 26: Tecnotion's 3 phase Ironless motor UC3

The Tecnotion linear motors of the UM, UL and UC series are cog-free 3 phase synchronous motors. They are designed compactly and have comfortable mounting tolerances. The motors are designed in specific N and S versions to provide a suitable motor for every possible supply voltage.

Some characteristics of these linear motor types are:

- Relatively high peak force,
- Excellent dynamics,
- Capable of speeds up to 15 m/s,
- No attraction force,
- No cogging,
- Murphy-safe design,
- Integrated temperature sensors for both safety and temperature measurement.