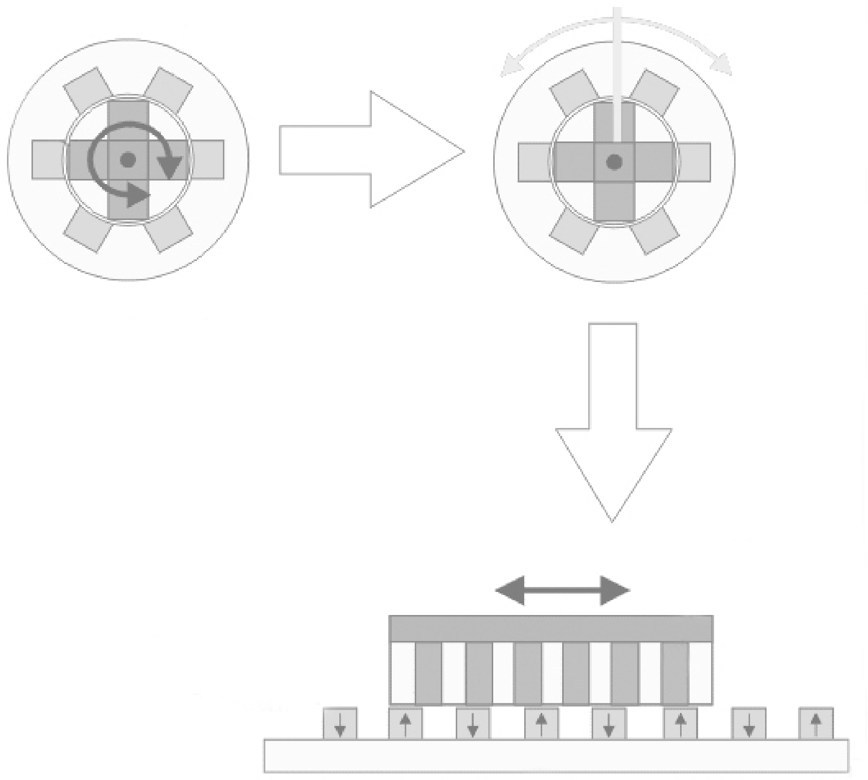

Information brochure

A primer of linear motors

Version: 1.1
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BECKHOFF

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1 Foreword

1.1 Notes on the documentation

This description is only intended for the use of trained specialists in control and automation engineering who are familiar with the applicable national standards.
It is essential that the following notes and explanations are followed when installing and commissioning these components.

The responsible staff must ensure that the application or use of the products described satisfy all the requirements for safety, including all the relevant laws, regulations, guidelines and standards.

Disclaimer

The documentation has been prepared with care. The products described are, however, constantly under development.
For that reason the documentation is not in every case checked for consistency with performance data, standards or other characteristics.
In the event that it contains technical or editorial errors, we retain the right to make alterations at any time and without warning.
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1.2 Documentation issue status

Issue	Comment
1.1	General update
1.0	First edition from October 2011

2 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.

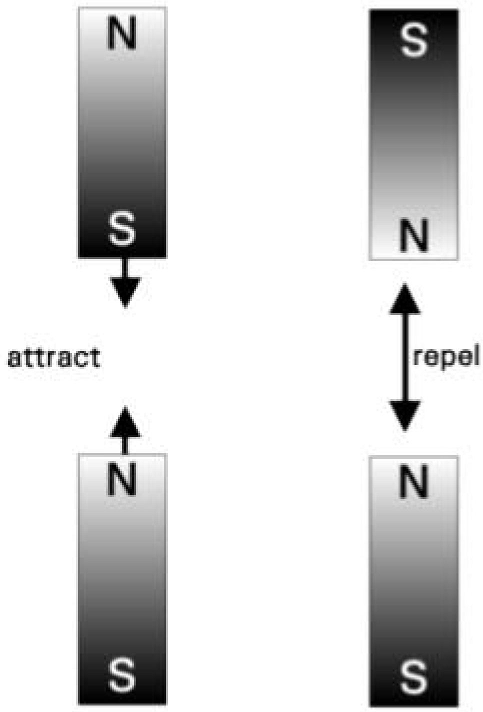
In this leaflet the following information can be found:

- 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 series AL2000 linear motor

3 Basic physical principles

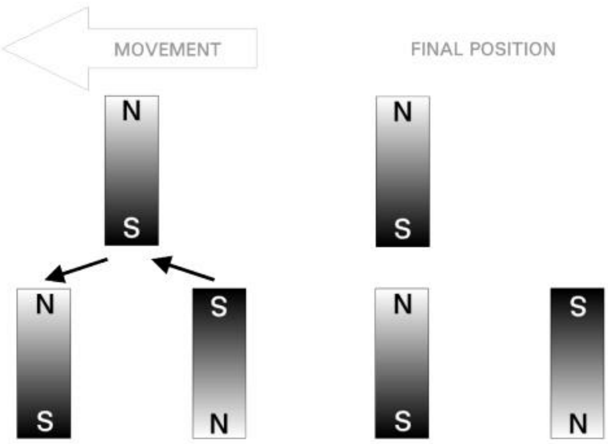
3.1 Magnetism

Attraction and repulsion:



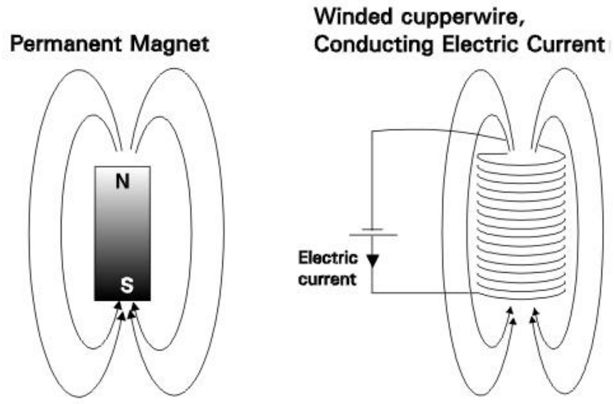
The operation of a linear motor is based on the principles of magnetism. When two permanent magnets are placed in opposition, they will apply a force to each other. Dependent on the position of the poles, they attract or repel each other. Equal poles are repellent and opposite poles are attracting.

Moving principle:



Suppose we have a movable but irrotatable magnet. The magnet only can be moved in a straight horizontal line. Now this magnet is positioned above two fixed magnets as shown left in the figure. Because of the attracting and repelling forces, 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. Changing the poles of the upper magnet, would make the magnet move back to the right.

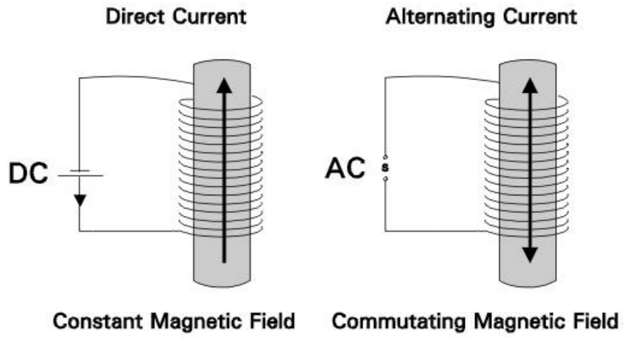
Physical resemblance of permanent magnet and electric coil:



A linear motor is propelled by similar attraction and repulsion forces. The changing the magnetical poles is enabled by using winded cupper wire, i.e. a coil, instead of a permanent magnet. 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:

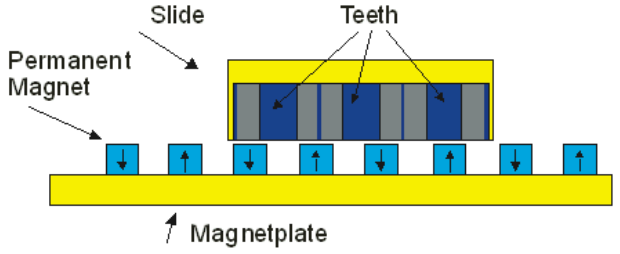
The amperage of the current, the number of windings, and the kind of core material.

Electromagnetic exiting of a constant and a commutating magnetic field:



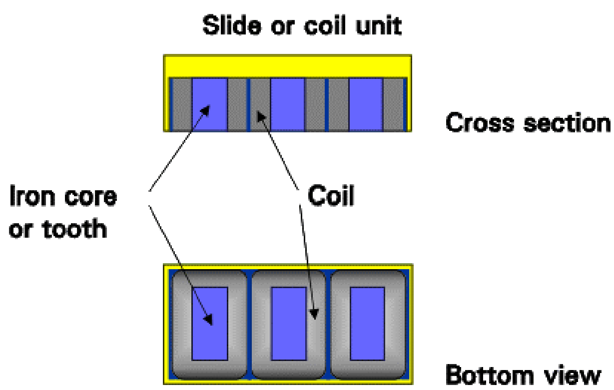
Generally iron is used as core material. Because of its very low magnetic resistance it has some very good characteristics for conducting the magnetic field. In fact the iron core can be considered as a magnet. In the case of a direct current the core behaves like a permanent magnet. In addition, reversing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

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. The linear motor type discussed in this leaflet has coils with an iron core (see following figure). These cores that act like magnets are called 'the teeth'. The coils are supplied with an electric current The slide is propelled 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.

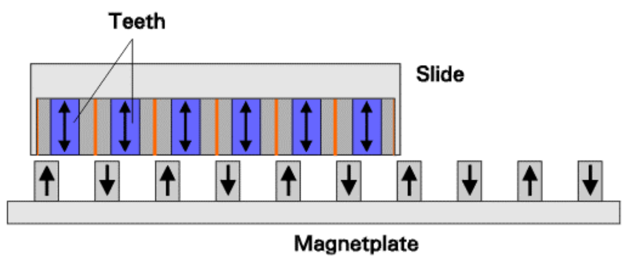
Linear motor, schematic cross section:



3.2 Phase linear motor

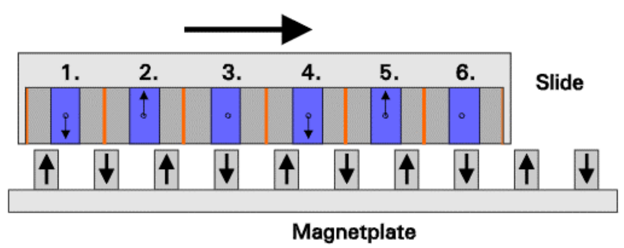
Different techniques can be applied in order to get an accurate and smooth motion of the slide. The permanent magnets are fixed on the magnet plate. So the phase of the magnetic force of each magnet is invariable. For the coils on the other hand the phase is adjustable. The slide is propagated by commutating 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 coils in respect to the permanent magnets.

Erroneous postioning and phasing



Placing the coils in the same pattern and mutual distance as the magnets, as shown in the figure is problematic. When in addition the coils are provided with equally phased current, the slide won't move at all. Considerations like these should be faced when designing a linear motor of series AL2000.

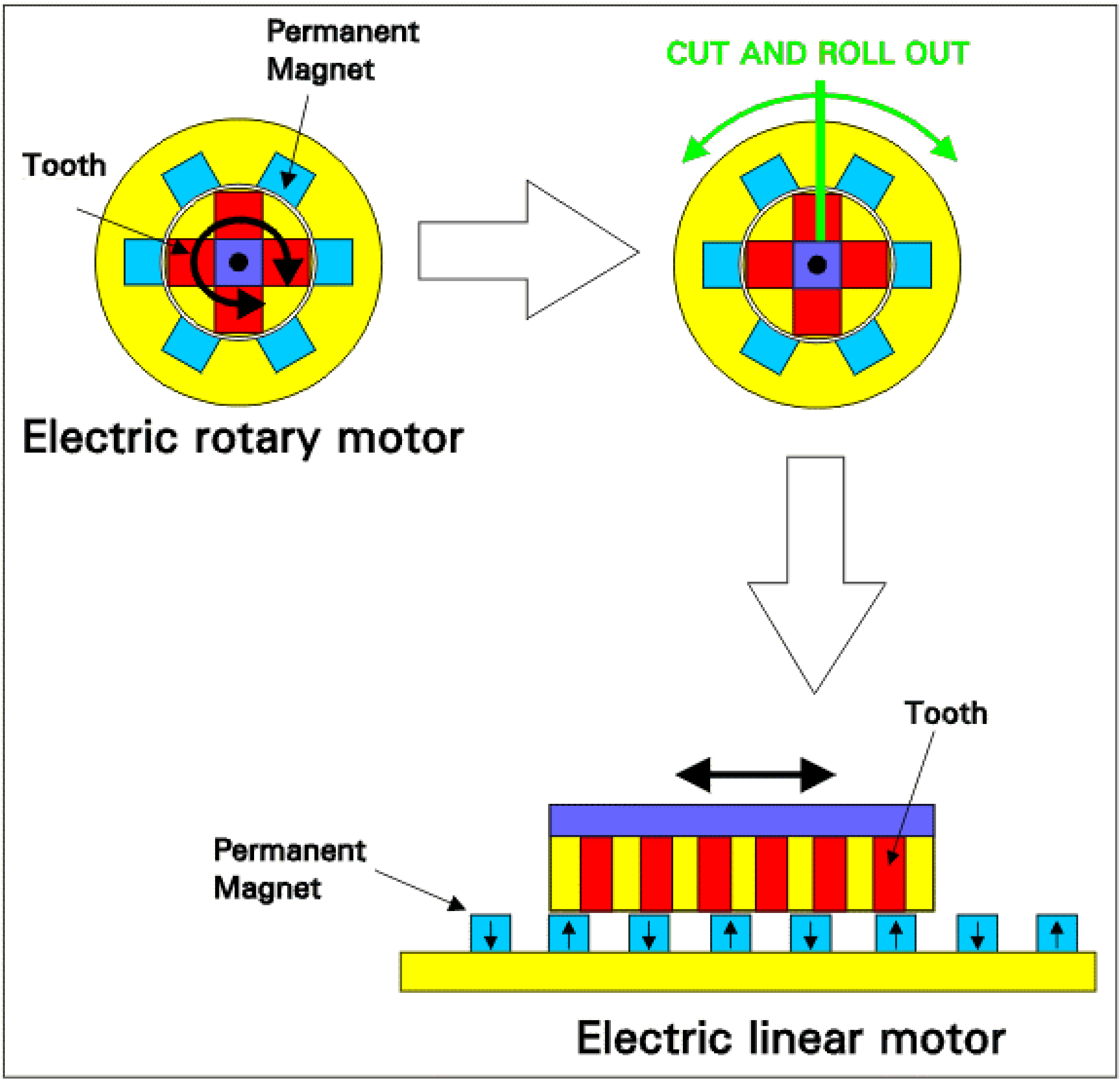
Postioning and phasing for a 3 phase linear motor



The principle of the three phase linear motor comes to meet the mentioned problems. In the example here discussed, the coils are equally positioned in the slide with a ratio 3 to 4 compared to the magnets of the magnet plate (see figure). As a result three different groups of coils can be distinguished. Coil 1 will continuously have a comparable position as coil 4. Coil 2 and 5 are also comparably positioned as well as coil 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. Information about this position is provided by a linear encoder.

3.3 Linear and rotary compared

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. In fact a linear motor is a rotary motor opened up and laid out flat (see figure). Hereby the function of the rotor is transformed in the slide function. 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, the linear motor directly provides it.

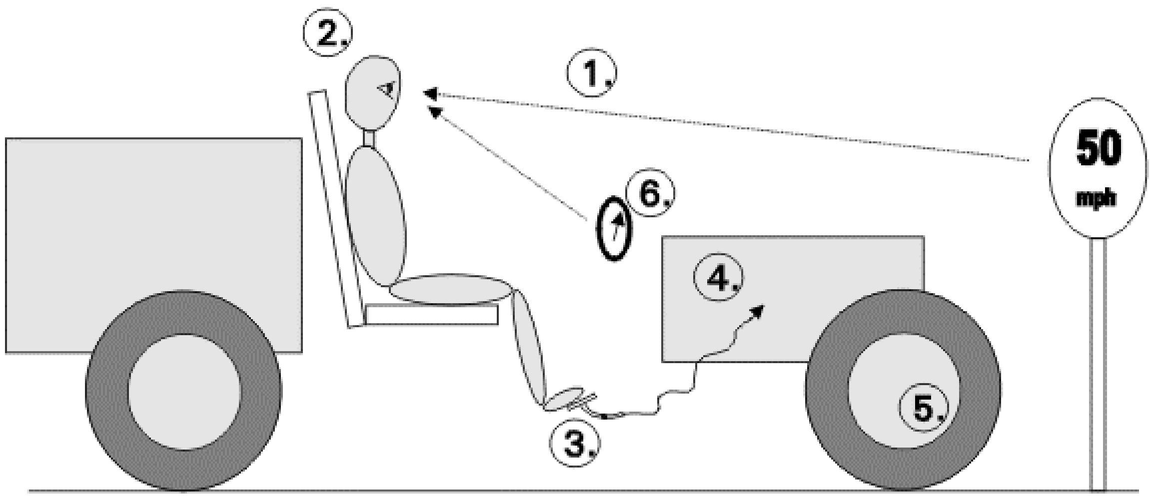
The direct drive results in some significant advantages.

- Accurate position control and response is possible at submicron level.
- 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 magnetplate. In the case of added length there are no speed limitations nor is there a higher inertia or lower dynamic stiffness.

4 Positioning

4.1 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.



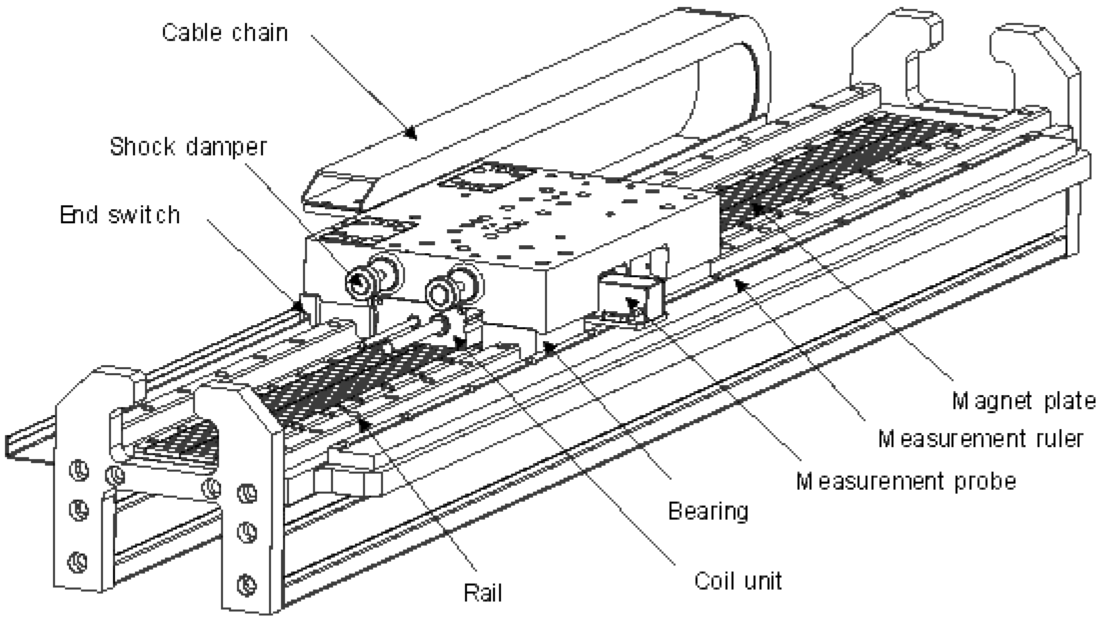
To have some impression of the positioning system a superficial comparison could be made with the speed control of an automobile. The information of the traffic sign (1) is detected and interpreted by the driver (2) and translated into an adjustment of the gaspedal (3). This results in an adjustment 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. 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.

When having an incremental feedback, the amplifier has no information about the positioning of the coilunit towards the magnets. Especially when starting a motor operation this could be problematical. Herefore the slide is activated to some minimal testmovement. This 'magnetic alignment' supplies the positioning system with the required information.

5 Linear motor system

5.1 Overview

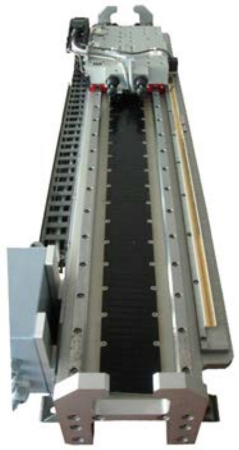


A linear motor usually is part of a bigger system. This system enables controlled movement. A complete linear motor system consist at least of the following parts:

- A mounting frame
- A magnet track build out of magnet plates.
- 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 malfunctions.

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

5.2 Practical considerations of linear motor systems



A part of a total machine concept

A linear motor of Beckhoff Automation GmbH & Co. KG is not a system on itself. 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 applicable 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 magnet plate 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 Beckhoff Automation GmbH & Co. KG.

Rails and bearings

To assure a free movement the slide is provided with bearings that run smoothly on two rails or with air bearings. The rails are mounted aside the magnet plate. 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 magnet plates a small tolerance is acceptable.

Heat dissipation

Especially in the coil unit the heat dissipation can be significant. Heat flow causes temperature differences. In some cases this could be unacceptable for accuracy or other reasons. So, special attention has to be given to the heat flow to the ambient. In some cases (water) cooling is needed.

Servo drives

Linear motors of the AL2000 series could ideally be combined with our 3 Phase servo drives of the AX5000 series. The servo drives AX2000 covers the complete rotary and linear motor range. The prepared motor-, feedback- and thermal-protection cables completes the full linear motor servo system. All default parameters of linear motor-controller combinations are defined and loadable.

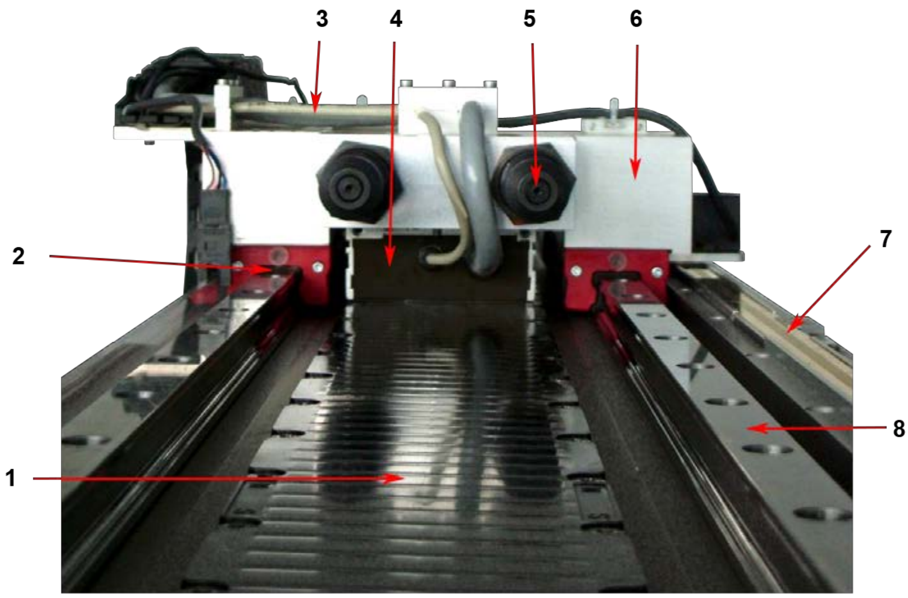
Accuracy

The accuracy of the positioning system 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 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 itself is an electromagnetic device. It deals with resistance and self-inductance. This implies that the current in the coils always lags behind the provided voltage signal. Since the magnetic force is directly linked to the current this means that the motor force also lags behind. All these items affect the accuracy of the linear motor, its small signal behavior.

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.



1. Magnet plate
2. Bearing
3. Cable
4. Coil unit
5. Damping
6. Slider
7. Linear ruler
8. Rail

Magnetic flux and distance

Just like a rotary motor a linear motor is propagated by an electromagnetically 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 magnet plate small. The gap can vary a little without losing much performance.

Cogging

The permanent magnets produce an attraction force to all magnetic materials in the vicinity. They also attract the coil unit. Because of the separate positioning of the magnets on the magnet plate, the magnetic field is not homogenous. So, dependent of the position of the magnets the motor force will be disturbed. Such position dependent disturbance could make the slide cog. Beckhoff Automation GmbH & Co. KG sophisticated design meets with the problems of cogging.

Note	**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 magnet plates. These plates should be handled with care and with proper tools. Beware of the fact that materials or clothes get jammed between magnet plate and iron objects. For mounting and dismounting purposes magnetic field neutralizing protection plates are to be used. Carefully follow the installation instructions of the applied servo controller and 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.

6 The series AL2000 linear motor

The motors of the AL2000 series are three phase iron core linear motors in a very compact design. Coils with iron core are mounted in the slide. The slide moves over the magnet plate. The small gap between the plate and the slide is established by the use of rails and bearings. Because of the small airgap the magnetic resistance between coils and magnets is low. This results in a high magnetic force.

Some characteristics of this linear motor type are

- High peak force (up to 6000 N).
- High continuous force.
- Relatively small attraction force
- Low heat dissipation.
- Low cogging.
- Dynamics and accuracy at an intermediate level.
- High speed (up to 10m/s).
- Moderate price of magnet plate.

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