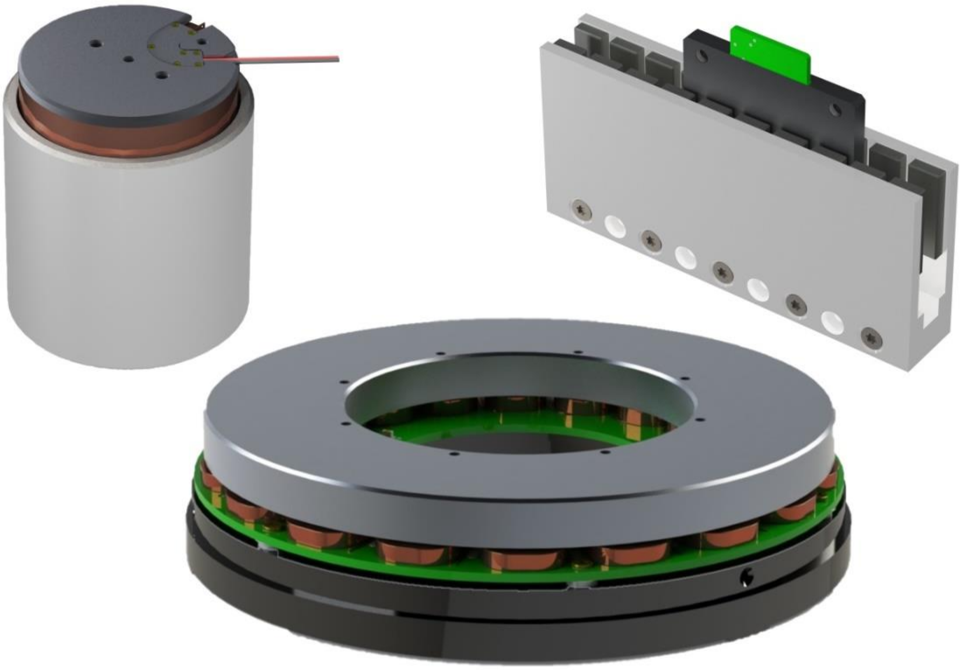
PIMag®: Voice Coil, Linear, and Torque Motors Developed In-house
-- Dr. Nico Bolse --

Individual design of magnetic direct drives for flexible, competitive, and application-specific positioning solutions



1 Introduction

Positioning and scanning systems with magnetic direct drives are suitable for applications that require high dynamics and repeatability and that work reliably even at high operating cycles.

PI has many standard and customer-specific positioning solutions on offer, which are equipped with magnetic direct drives, and the company has many years of experience in the design, construction, and manufacture of the necessary mechanical and electronic components, including proprietary encoders, guides, and motion controllers.

PI can also develop proprietary motors if required. For example, if standard series or customer-specific solutions need to achieve specific performance characteristics that cannot be reached by using drive components currently available on the market. Here, the main focus is on voice coil motors, ironless and iron-core linear motors, and torque motors.

PI can provide customers with a competitive and flexible solution that is precisely tailored to the requirements of their application thanks to its expertise in motor development and its high vertical range of manufacturing.

The motors developed in-house are identified by the PIMag® brand name. PI's positioning systems and scanners that use these motors are labelled: Driven by PIMag®.

This paper explains the functional principle and properties of voice coil, linear, and torque motors. Furthermore, it uses examples to show how the performance characteristics of the various motor types can be adapted to the specific requirements of the positioning solution through an individual design, e.g., to achieve a high force density or a compact design.

2 Magnetic Direct Drives

Voice coil, linear, and torque motors work due to different physical principles. For example, voice coil drives are based on the Lorentz force in which the force generated is proportional to the magnetic field strength and to the current of the current-carrying conductors. The electrical energy is converted here into mechanical energy. The generated force acts bidirectionally depending on the direction of the current.

Direct drives offer advantages, especially in regards to wear and dynamics, compared to common drive screw-based technologies. Since they use as few mechanical components as possible, less friction and zero backlash are the result and they, therefore, achieve a higher precision.

2.1 Voice Coil Motors

Cylindrical voice coils are constructed according to the plunger coil principle, i.e., the winding body sits in a field assembly as indicated in Figure 1. Either the winding body ("moving coil") or the pot ("moving magnet") can be moved.

These voice coils can also be designed with a hollow shaft which can be used as a feedthrough or can be used to integrate a linear guide.

Abb. 1 PIMag® cylindrical voice coil motor for use in medical endoscopes

Besides cylindrical designs, flat designs can be realized. In this case, the winding body moves over parallel magnets as shown in Figure 2.

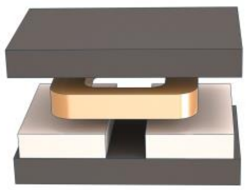


Abb. 2 Voice coil motor with a flat design

Voice coil motors are suitable for positioning tasks with high dynamics and high forces. They are used primarily in scanning applications with travel ranges up to several tens of millimeters. For example, the V-522, V-524, and V-528 linear stage series (as shown in Figure 3) are based on voice coil motors from PI.

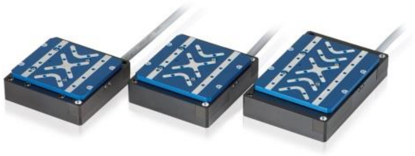


Abb. 3 Driven by PIMag®: V-522, V-524, and V-528 linear stage series with flat-design voice coil motors from PI

Voice coils can also be optimized for force or motor constant. The motor constant denotes the ratio of force to power loss. The higher the motor constant, the less heat is produced when a certain force is generated. It, therefore, also describes the efficiency of the motor in regard to converting electrical into kinetic energy. However, as the temperature rises, the winding resistance and, therefore, also the power loss increase, which is why the motor constant is temperature-dependent.

PI has developed cylindrical motors, as shown in Figure 4, to maximize the motor constant.

Abb. 4 PIMag® cylindrical voice coil motors

They are characterized by a maximized ratio of motor constant to installation space and can be manufactured in various sizes. Cylindrical motors are used, for example, in positioning solutions for focusing devices in order to dynamically move a measuring head or an optical system vertically by means of a flexure. Table 1 shows the performance characteristics of three examples in different sizes

Performance characteristics	Size 1	Size 2	Size 3	Unit
Travel range	10	15	20	mm
Peak force	80	614	1772	N
Nominal force	20	149	380	N
Motor constant	7.5	31	57	N/√W
Force constant	22.6	88	98	N/A
Back EMF	22.6	88	98	Vs/m
Current at peak force	3.5	7	18	A
Current at nominal force	0.9	1.7	3.9	A
DC resistance	9.2	8.1	2.9	ohm
Inductance	4.5	7.5	3.4	mH
Electrical time constant	0.49	0.93	1.17	ms
Mechanical time constant	1.71	0.66	0.54	ms
Runner mass	95	630	1800	g
Stator mass	235	2530	8800	g

Tab. 1 Examples of cylindrical voice coil motors developed in-house

The force depends on the position since the coils move in relation to the permanent magnets along the travel range. This can be seen in Figure 5.

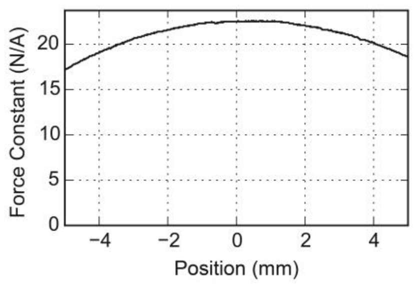


Abb. 5 Force-displacement diagram of a cylindrical PIMag® voice coil motor

In order to drive the force into the motor as quickly as possible, the voltage can be increased as shown in Figure 6. In this way, the current is then made available correspondingly faster. The acceleration then increases in the same ratio. Highly dynamic applications are, therefore, possible through a fast increase in acceleration (jerk).

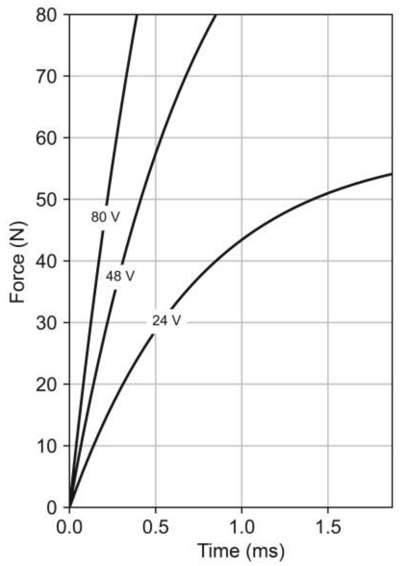


Abb. 6 Force-time diagram of a cylindrical voice coil motor developed in-house

2.2 Linear Motors

A classical 3-phase linear motor is basically a series of at least three (or a multiple of three) voice coil motors which are controlled, i.e. commutated, according to a position-dependent, fixed pattern. A motor consisting of three coils in a U-shaped magnetic track is illustrated in Figure 7.

Abb. 7 Structure of a linear motor: Three current-carrying magnetic coils move in a magnetic track or vice versa

Optionally, PI encapsulates its linear motors under vacuum. This results in an improved heat dissipation, whereby higher nominal forces can be achieved. In addition, the sealing compound ensures that the motor is encapsulated and therefore protected against external damage, e.g., during assembly.

For special applications that require high velocities or fast current rise times, PI can design motors for very high operating voltages of up to 600 VDC. In this regard, linear motors benefit from the same effect that was previously described for voice coil motors: Due to the higher voltage, the current can be made available faster, resulting in increased motor dynamics. It is also possible to use typical industrial servo amplifiers with high voltages.

The magnetic tracks used in PI linear motors are available in various lengths. They can be used as modular elements and arranged in series in order to realize any desired travel range. Single-sided or U-shaped magnetic tracks are available. U-shaped magnetic tracks achieve higher magnetic field strengths and higher forces than single-sided magnetic tracks. If the magnets are additionally arranged as a Halbach array, the magnetic field strength can be increased by about 10% compared to a North Pole to South Pole arrangement. In addition, the iron counterplate can be omitted in a Halbach array, making these magnetic tracks significantly lighter. The advantages of using a Halbach array also apply to single-sided magnetic tracks. In this case, the use of Halbach arrays avoids the generation of high stray fields on the back of the single-sided magnetic track. PI can provide carbon supports for applications that require ultra-light magnetic tracks.

PI manufactures both ironless and iron-core linear motors. For example, motors of both types are used in the V-508 linear stage series. An example of a linear stage of this series is shown in Figure 8.

Abb. 8 Driven by PIMag®: Linear stage of the V-508 series based on PI's proprietary linear motor with Halbach array for a particularly flat design with both low weight

2.2.1 Iron-Core Linear Motors

Iron-core linear motors are suitable for applications requiring high forces and accelerations with limited installation space. The iron maximizes the magnetic forces and contributes to high thermal stability. To reduce eddy current losses, the iron is laminated and it is mostly made of stacked and insulated transformer plates. The disadvantage of iron-core motors is the attraction force that arises between the iron and the magnets arranged on the opposite side. This is increased further still if a linear guide is used. "Cogging" is also a problem since the displacement force varies over the travel range – while this can be minimized by means of special tooth geometries, it cannot be completely eliminated. An example of an iron-core linear motor is shown in Figure 9.

Abb. 9 Example design of an iron-core linear motor without a magnetic track

The sealed motor shown in Figure 10 is an example of a proprietary linear iron-core motor developed by PI.

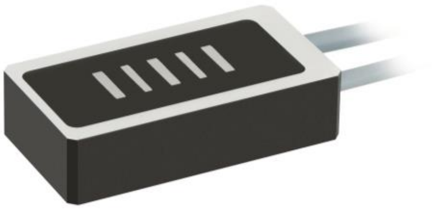


Abb. 10 PIMag® linear motor with laminated magnetic steel and epoxy-resin sealing

The iron-core linear motors, for example, are constructed with three or six coils. The performance characteristics are illustrated by two examples in Table 2.

Performance characteristic	3 coils	6 coils	Unit
Max. voltage	48	48	V
Nominal force (with/without cooling)	5.8 / 12.5	9.0 / 22.7	N
Nominal current (with/without cooling)	1.2 / 2.6	1.0 / 2.5	A
Motor constant	4.59	6.27	N/√W
Force constant	4.81	9.08	N/A
Back EMK (Phase-Phase)	3.75	7.5	Vs/m
Resistance (phase-phase)	2.1	4.1	ohm
Inductance (phase-phase)	1.64	3.79	mH
Electrical time constant	0.78	0.92	ms

Tab. 2 Sealed linear motors with three or six coils

To ensure a constant force, the linear motors can reach a specified maximum speed. This is shown in Figure 11 with the example of an iron-core linear motor. In addition to other motor data, this maximum speed also depends on the motor voltage provided.

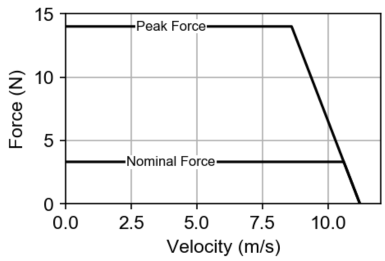


Abb. 11 Force-speed diagram of an iron-core linear motor

2.2.2 Ironless Linear Motors

Ironless linear motors are suitable for positioning tasks with the highest demands on precision. Unlike with iron-core linear motors, cogging does not occur. This makes ironless motors ideally suited for applications requiring high travel accuracy and speed stability because there are no varying forces on the linear guide or cogging-related disturbances for the controller. They are also suitable for the smallest installation spaces thanks to their particularly flat design. Power and dynamics requirements can be met by increasing the number or dimension of the motor coils.

In most cases, ironless motors achieve lower nominal and peak forces than iron-core motors. This is due to the lack of thermally conductive metals in the design and the resulting limited heat dissipation from the coils. However, the motors are protected against overload by means of additional temperature sensors. An example of an ironless linear motor is shown in Figure 12.

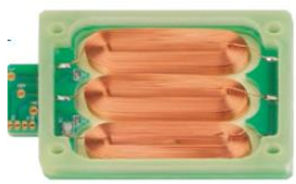


Abb. 12 Example design of an PIMag® ironless linear motor without a magnetic track

The flat motor with a U-shaped magnetic track shown in Figure 13 is an example of a proprietary ironless linear motor developed by PI.

Abb. 13 Flat PIMag® linear motor with three coils and u-shaped magnetic track

The ironless motors, for example, are also constructed with three or six coils. The performance characteristics are illustrated by two examples in Table 3.

Performance characteristic	3 coils	6 coils	Unit
Max. voltage	48	48	V
Nominal force (with/without cooling)	4.1 / 9.8	8.1 / 18.4	N
Nominal current (with/without cooling)	0.5 / 1.2	1.0 / 2.3	A
Motor constant	4.56	6.45	N/√W
Force constant	7.9	7.9	N/A
Back EMK (Phase-Phase)	6.5	6.5	Vs/m
Resistance (phase-phase)	6.1	3.1	ohm
Inductance (phase-phase)	0.87	0.42	mH
Electrical time constant	0.14	0.14	ms

Tab. 3 Especially flat motors with three or six coils

2.3 Torque Motors

A torque motor can simply be thought of as a radially designed linear motor. In an alternative design, the rotor can also be represented as a rolled-up, single-sided magnetic track, while the stator houses the coils which are embedded in an iron matrix. An example of a torque motor developed by PI is shown in Figure 14.

Abb. 14 Extremely flat PIMag® torque motor with large aperture

Like linear motors, torque motors are well-suited to positioning tasks in which the highest demands for precision need to be combined with high torques and accelerations. While the magnet length scales linearly, the torque scales quadratically with the diameter. In addition, large diameters allow apertures, e.g., for the passage of laser beams or cables.

Torque motors are zero-play direct drives which are, therefore, suitable for positioning applications that require the highest accuracy. The high stiffness leads to a high repeatability. The high drive torque enables high acceleration and leads to high dynamics.

In precision positioning, torque motors are mainly used for direct drive rotation stages. Such a rotation stage is shown in Figure 15, stacked on a hexapod. This example shows an extremely flat, highly dynamic, and stable torque motor rotation stage with a very large aperture. The common aperture of the rotation stage and the hexapod can be used, e.g., as a feedthrough.

Abb. 15 Flat PIMag® torque motor rotation stage with large aperture stacked on a PI hexapod

Another example is the torque motor rotation stage, shown in Figure 16, which is mounted on the H-811 PI hexapod for use in highly automated production systems.

Abb. 16 PIMag® torque motor rotation stage stacked on a PI hexapod for highly automated production systems

3 Summary

With the in-house expertise to develop proprietary motors and with the core technologies needed for a complete positioning solution, such as sensors, guides, and motion controllers, PI offers its customers competitive solutions with performance characteristics that are optimally adapted to the requirements of the application. Figure 17, for example, shows an application that combines different motor types. The multi-axis setup for autofocus applications shown, consists of an X and a Z axis. The X axis, for example, holds a workpiece that is to be machined on a V-508 linear stage. As a supplement to the commonly used piezoceramic drives, the voice coil Z axis enables long travel ranges up to several millimeters. This is important, among other things, for laser material processing. Travel ranges of 1 to 7 mm are typically also required for multiphoton fluorescence microscopy and deep tissue microscopy. Furthermore, voice coils offer particularly high maximum speeds which can, for example, be used to increase throughput when using “scanning-on-the-fly mode” in digital slide scanning processes.

Abb. 17 Autofocus application with voice coil on the Z axis and linear motor on the X axis

However, thanks to PI's vertical range of manufacturing and technological range, PI is the ideal partner even when customers only require one single component of a positioning solution.

4 Author

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5 PI in Brief

Well known for the high quality of its products, PI (Physik Instrumente) has been one of the leading players in the global market for precision positioning technology for many years. PI has been developing and manufacturing standard and OEM products with piezo or motor drives for more than 40 years.
Continuous development of innovative drive concepts, products, and system solutions and more than 200 technology patents distinguish the company history today. PI develops, manufactures, and qualifies all core technology itself: From piezo components, actuators, and motors as well as magnetic direct drives through air bearings, magnetic and flexure guides to nanometrological sensors, control technology, and software. PI is therefore not dependent on components available on the market to offer its customers the most advanced solutions. The high vertical range of manufacturing allows complete control over processes and this allows flexible reaction to market developments and new requirements.

By acquiring the majority shares in ACS Motion Control, a worldwide leading developer and manufacturer of modular motion controllers for multi-axis drive systems, PI can also supply customized complete systems for industrial applications that have the highest demand on precision and dynamics. In addition to four locations in Germany, the PI Group is represented internationally by fifteen sales and service subsidiaries.