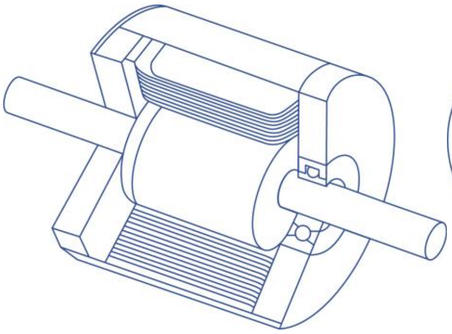
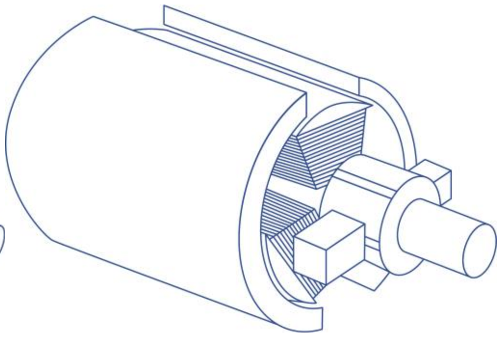
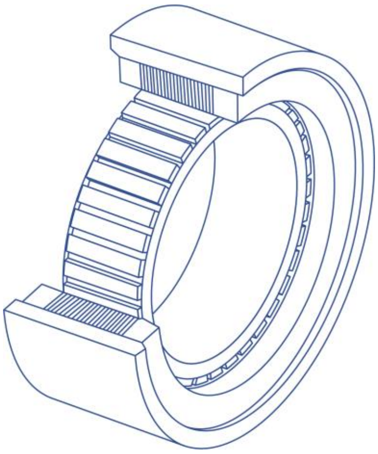
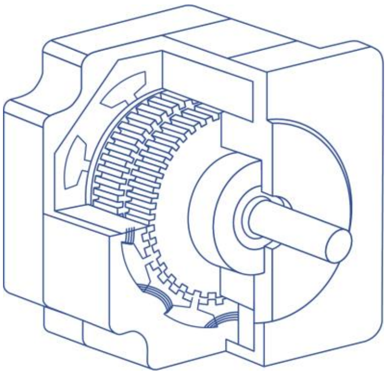
Rotating Electric Motors for Precision Positioning

An application-related comparison of different motor types









Contents

1 Introduction

Rotating electric motors are typical drives for precision positioning. In positioning systems, they are usually applied together with a lead screw or ball screw to translate the motor's rotary motion into a linear motion. Every motor type has different strengths and weaknesses. This white paper discusses an application-related comparison of different motor types used by PI and also describes design and function of these different motors.

2 DC Motor (DC)

Direct current motors offer **good dynamics** over a large speed range, **low heat generation,** as well as **smooth and vibration-free operation**. For example, in a positioning solution, a drive screw pitch of 1°mm/per revolution results in a typical travel velocity of approximately 50 mm/s. However, the wear-prone brushes used to commutate the motor can be a disadvantage with a short **lifetime** of **1,000 to 5,000 hours**.

Applications in a **vacuum** are only possible up to **10^{-6} hPa**, otherwise the humidity is lacking that is required by the carbon brushes for commutation. Moreover, the brushes exude **carbon dust**; a problematic effect in vacuum, clean rooms, and optical applications.

2.1 Standard Configuration

A DC motor exploits the force effect of the electrical current via a rotatable conductor loop in a magnetic field. The **movement** is caused by the **Lorentz force**, resulting from the charge carriers in the electromagnetic field. With the help of the right-hand-rule, as shown in figure 1, it is possible to establish the direction of the force relative to the direction of the current and the magnetic field.

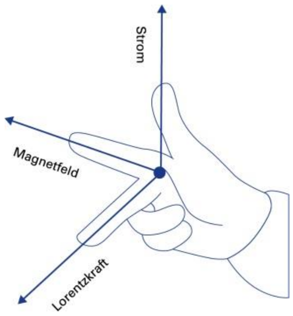


Fig. 1 With the help of the right-hand-rule, it is possible to establish the direction of the force relative to the direction of the current and the magnetic field.

PI mainly uses **permanent DC motors** with conductor loops reeled up on a coil and mounted as a rotor within a stator. The stator's permanent magnets provide the poles.

In order for the motor to perform a revolution, the applied direct current is transformed to an alternating current. This is achieved with a **commutator**; e.g., in its most basic version, a segmented slip ring. Additional **carbon brushes** turn the current in the rotor winding, which results in an alternating current that maintains the direction of force with continued movement. Figure 2 shows an example of a permanent DC motor design.

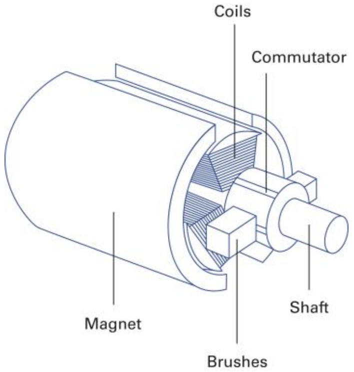


Fig. 2 DC motor design with stator magnet, rotor windings, commutator, brushes, and motor shaft.

2.2 Operating Behavior

Figure 3 shows a simplified model of the rotor circuit of a DC motor with inductance, resistor, and voltage source.

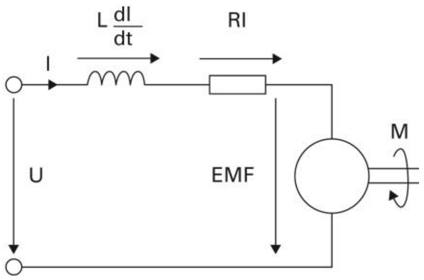


Fig. 3 Simplified rotor circuit equivalent diagram of a DC motor with inductance, resistor of the rotor winding, and rotor voltage.

This results in a motor voltage according to the law of induction:

$$U = L\frac{d\,I}{dt} + RI + EMF$$

L is the winding inductance, I the motor current, R the winding resistance, and EMF is the **induced voltage counteracting the motion**. This is described as the **back electromotive force (back-EMF)**. This force acts **proportional** to the **rotational speed**. When the back-EMF equals the motor voltage, the maximum rotational speed will be achieved. In DC motors, the voltage drop over the inductance can be neglected, resulting in a **proportionality** of **voltage** and **rotational speed**, where the **sign** of the voltage determines the **direction of rotation**:

$$U = RI + k\phi 2\pi n$$

k is the motor constant, ϕ is the magnetic flux in the air gap, and n is the rotational speed. Accordingly, the **torque**

$$M = k\phi I$$

is **proportional** to the **current**. A combination of both equations results in a decrease of the rotational speed under load that is proportional to the torque. This is illustrated in figure 4 with the **torque-speed characteristic**.

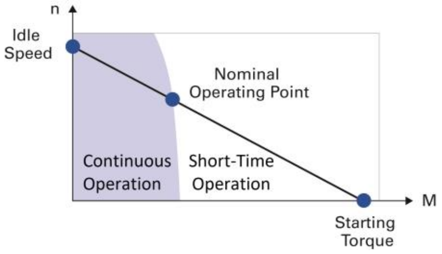


Fig. 4 Torque-speed characteristic of a DC motor with idle speed, nominal operating point, starting torque, short-term, and long-term range.

2.2.1 Continuous Operation

A **powerful motor** is identified by a **flat characteristic curve** because the rotational speed is **more resistant to load changes**. In order to shift the characteristic curve up while maintaining the gradient, i.e., a higher **idle speed** and a higher **starting torque**, either a thicker copper wire will be required for the winding or a higher voltage during operation. Generally, continuous operation is only permissible with limited torque speed. The **intersection** between **continuous operation** and **short term operation** with the torque-speed characteristic curve equates the **nominal operating point**.

2.2.2 Short Time Operation

The maximum permissible overload during short term operation is limited by the maximum permissible winding temperature. However, it is possible to irrevocably de-magnetize the permanent magnets by very high currents. Mounting position, convection, ambient pressure (vacuum), etc. may also pose limitations. Generally, the permissible residence time in the short term operation is **one to three seconds** and is signified by the **thermal time constant of the winding** and the **extent of the overload**. Figure 5 shows an example of typical values.

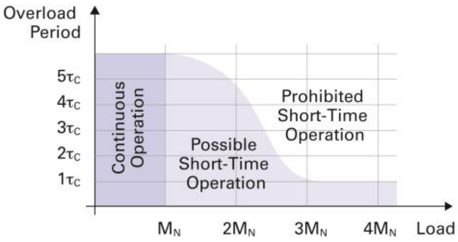


Fig. 5 Overload periods in multiples of the thermal time constant of the winding over the overload in multiples of the nominal torque to illustrate the continuous and short-term operation of a DC motor.

Higher loads result in increased motor losses due to the proportionality of torque and current, leading to a higher operation temperature. For a quick estimate of the **temperature changes**, the **current heat losses**

$$P_L = RI^2$$

can be multiplied by the **thermal resistance** from the corresponding **motor data sheet**. Should the motor be operated at its thermal limits, a closer examination is required. The motors are **limited thermally** by the surrounding temperature as well as maximum **winding temperatures**.

2.3 Position Control

DC motors require position encoders, e.g., **incremental** or **absolute encoders**, for **positioning tasks**. A motor can be operated in a **closed servo loop** when encoder signals are returned to a **controller**. In this manner, high position

resolution, constant feed, and a large dynamic range can be achieved. Basically, so-called **DC servo motors allow for the control of position, torque and velocity**. However, due to the feedback loop, **position jitter** occurs when the motor tries to keep a position.
Figure 6 shows an example of a closed loop. Normally, a rotary encoder is used on the motor shaft for the speed control of DC motors. An additional linear encoder on the motion platform can be deployed for position control.

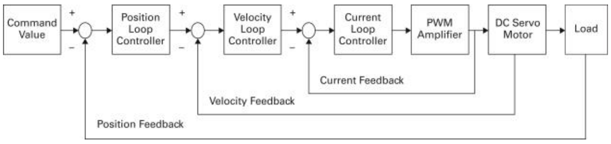


Fig. 6 Example of a closed loop for DC servo motors.

2.3.1 Dual-Loop Controller

In so-called **dual loop controllers**, as offered by **ACS Motion Control**, the **linear encoder** can be deployed for **both position and velocity control at the same time**. This is an advantage when a rotary encoder would limit the minimum incremental motion due to low resolution. However, this also reduces the bandwidth of the velocity control loop because the linear encoder registers the oscillations of the motion platform to a higher degree than the rotary encoder on the motor shaft.

3 DC Motor with ActiveDrive (PWM)

PI has developed the **ActiveDrive technology** for the control of motors with a rated power exceeding the **controller's output power** to realize **higher velocities**. To this end, an amplifier is integrated with the motor in a shielded case. The controller triggers the **integrated amplifier** via a **pulse width modulation (PWM)**. The motor power will be controlled by the ratio of on/off-duration, as shown in figure 7. This requires an additional power adapter for the amplifier and optimized heat dissipation to maintain precision.

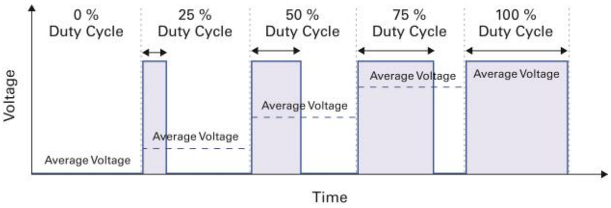


Fig. 7 Pulse width modulation (PWM) for various on/off-duration options.

4 Brushless DC Motor (BLDC) / Synchronous Servo Motor (SSVM)

Due to their **brushless commutation**, BLDCs (brushless direct current) and SSVM (synchronous servo motors) respectively, provide many advantages compared to brush DC motors:

- The **lifetime** is mainly limited by the bearings and ends after **several ten thousand hours.** As a consequence, the motors are **more reliable.**
- The brushless design allows for a motor that is **smaller, lighter, more efficient, and low-maintenance** while providing the same performance; resulting in a **large torque/motor size ratio**.
- The electronic commutation allows for **high dynamics** at **low temperatures** with **few vibrations**.

These are the reasons why BLDCs and SSVMs are preferred in **industrial applications** instead of DC motors.

4.1 Motor Design

Despite its name, the motor design does not correspond to the design of brushless DC motors but rather to the design of a **permanent-magnet synchronous machine**. This is the reason why BLDC motors are often referred to as SSVM, for example when used as industrial motors operating in the low-voltage range. The term BLDC emphasizes the brushless commutation whereas the term SSVM stresses the rotor movement synchronous to the rotating magnetic field. However, the terms BLDC and SSVM are often used interchangeably. Sometimes, a difference is made based on the **control type (block or sinusoidal commutation)**; in this scenario, block commutation refers to a BLDC motor, and sinusoidal commutation to an SSVM. Figure 8 shows an example of the corresponding motor design.

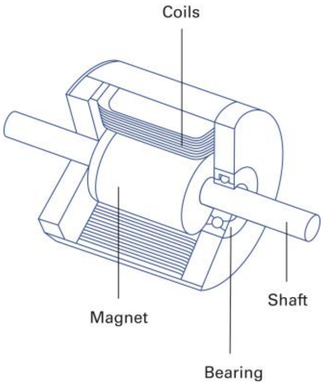


Fig. 8 Design of a BLDC and SSV motor, respectively with rotor magnet, stator winding, bearing, and motor shaft.

The stator carries the winding that creates a rotating magnetic field after electronic activation to drive the permanent magnet rotor; this means that **commutation** is purely **electronic**. For this reason, this motor is often termed electronically commutated motor (EC motor), too. Here, the rotor moves synchronous to the alternating current of the stator winding, i.e.

$$n = \frac{f}{p}$$

The **speed** can only be influenced by the **frequency f** or the number of pole pairs p. Since the number of pole pairs is prescribed by the motor design, the **speed setting** can only be changed via the frequency during operation. In a servo amplifier, this is typically achieved by a **change in voltage**.

4.2 Operating Behavior

The operating behavior corresponds to a synchronous machine where the current controller switches relative to the rotor dependent on the actual pole position. In this mode, the **speed can perform non-linear changes dependent on the load**. Figure 9 illustrates this in the torque-speed characteristic curve.

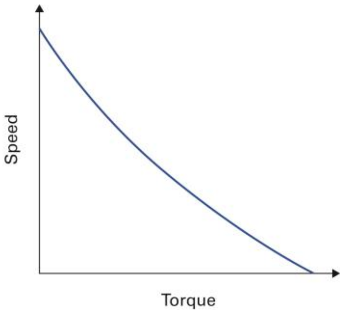


Fig. 9 Speed-torque characteristic curve of a BLDC respectively SSVM motor.

Apart from this, the operating behavior is similar to that of a DC motor. This explains the origin of the name of the brushless DC motor despite the deviating motor design.

4.3 Determination of the Rotor Position

In order to operate the motor synchronously at maximum torque, the stator and rotor magnetic fields need to be perpendicular to each other at all times. To achieve this, the **rotor position** needs to be known.

4.3.1 Sensor-Aided Determination of the Rotor Position

Since stator and rotor have neither mechanical nor electric contact, the relative rotor position needs to be determined with the help of **hall sensors**, for example. A directed magnet switches these sensors in the exact moment when the current in the winding is turned.

4.3.2 Sensorless Determination of the Rotor Position

Alternatively, it is possible to determine the rotor position sensorless by **measuring the back-EMF**. However, this method requires a specific startup process as the back-EMF completely vanishes at standstill. Furthermore, this method is only suited to **continuous operation at high speed**; otherwise the amplitude of the back-EMF would be too low. Typically, the rotor position is determined with the help of sensors.

4.4 Block Commutation

If the rotor position of a **three-phase** motor is determined by **three hall sensors**, offset by 120° to one another, the signal combinations are clearly defined for each rotor position at 60°. In **block commutation**, the **current** between the phases will be **switched in blocks**, i.e., in six steps **of 60° each** for the duration of one complete revolution. It is a disadvantage, however, that the magnetic stator field is only stable over 60° while the rotor field continues its revolution due to the turning permanent magnet. Consequently, the **magnetic fields are not always perpendicular to each other**. Placing the hall sensors in the center of the two switchover points will result in a phase displacement of 30° each, decreasing the torque by approximately 13,4%. These **torque ripples** occur with a six-fold electric rotation frequency of the motor, causing **vibrations** and **noises**. Figure 10 shows an illustration of block commutation and the resulting torque ripples.

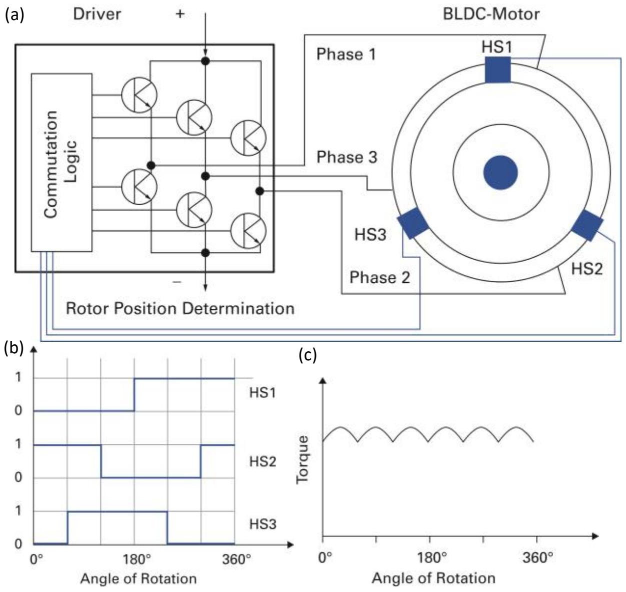


Fig. 10 (a) Block commutation principle on a BLDC motor. (b) Hall sensor signals HS1, HS2, and HS3, (c) torque ripple.

4.5 Sinusoidal Commutation

Smoother motion can be achieved with **sinusoidal commutation** where the **sinusoidal current introduced into each motor winding is phase-shifted by 120°**. When only hall sensors are being deployed for the determination of the rotor position it is possible to avoid torque ripples for the most part with the help of interpolation between the switchover points. Usually however, an additional encoder is used for the rotor position measurement and, as a consequence, the controller currents can be controlled in more detail. In this scenario, hall sensors are redundant or may be used for the determination of the phases respectively. The described operation is possible with PI's C-891 controller, SMC Hydra controller, as well as controllers from ACS Motion Controller.

4.6 Field-Oriented Control

In the case of sinusoidal commutation at high rotor speeds, the calculated currents may lag behind the actual rotor position as a result of limited control bandwidth, which means that the **stator and rotor field** are no longer **exactly perpendicular to each other at all times**. This can be avoided by **field-oriented control, also called vector control**. This is achieved by controlling the current vector in a rotating coordinate system of the rotor. This allows **extended speed and positioning accuracy** to be achieved. This type of operation is possible for example, with the PI C-891 controller as well as controllers from ACS Motion Control.

5 Torque Motor (TQM)

Torque motors are **zero-play drives** with often large radial dimensions. They can have a **very flat** design. The large radial dimensions allow for hollow shafts and **large apertures**, respectively, e.g., to conduct laser beams and cables. The zero-play allows **high positioning accuracy** and high drive rigidity, resulting in **high repeatability**. The **high drive torque** enables **high acceleration** and therefore **high dynamics**. Additional features include **high torsional rigidity, high peak torques, high degrees of efficiency,** as well as **very smooth running**.

Among others, torque motors are suitable for **high load applications on multi-axis or rotation stages** thanks to their compact design with respect to torque and rotational symmetry.

5.1 Motor Design

Torque motors are **permanent-magnet synchronous motors** where the load is directly connected to the rotor, i.e., zero-play. In other words, a torque motor is similar to a **wound up linear motor or a short-dimensioned BLDC motor, with a large diameter**. In comparison to the other discussed motor types, the torque motor is usually deployed as a **direct drive** for rotation stages. Figure 11 shows the motor design.

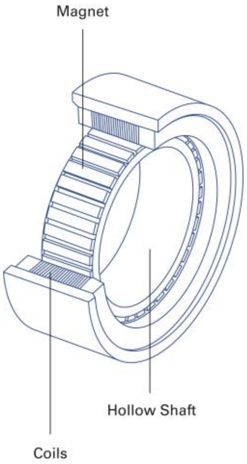


Fig. 11 Torque motor design, similar to a wound up linear motor or short BLDC motor.

Due to the center-based hollow shaft, this motor is sometimes referred to as a **hollow shaft motor**. This usually refers to a drive screw combination, allowing a particularly compact drive design for linear stages. As a result, this is no longer a direct drive because the load is no longer directly connected to motor.

The design of torque motors differs from BLDC motors with respect to the **large number of pole pairs**, accounting for **high torques** at medium and high speed.

The torque increases according to a so-called rule that applies to induction machines and therefore to the following proportionality:

$$M \sim A \cdot B \cdot l \cdot D^2$$

A is the current coverage in the stator winding, B is the flux density in the air gap, l is the active motor length and D is the rotor diameter. For this reason, **increased torque** in torque motors results in a **large diameter.**

In torque motors, the rotor typically carries the magnets and the stator carries the coils that are embedded in the iron matrix. Often, the coils are applied in three phases in **star connections**. However, a delta connection application is generally also possible.

- A star connection signifies a **higher torque constant**, i.e., more torque is being achieved with the same amount of current.
- The **delta connection** allows for a **higher speed constant**, i.e., the same speed is being achieved with less voltage.

6 2-Phase Stepper Motor (2SM)

Stepper motors only take **discrete positions** within one revolution. Due to their quantized steps, stepper motors only offer **reduced dynamics compared to DC motors**. High speeds can only be achieved with a large number of steps at the expense of the torque, because the windings need to be energized against one another in order to set the intermediate steps.

Stepper motors can be set up for applications in **vacuum**, have a **long lifetime**, and can be applied for **positioning tasks without the requirement of an encoder**. Open-loop operation of stepper motors does **not cause position jitter** because it is caused by the feedback loop in closed-loop operation. Often, a **mechanical damper** is applied in the form of a **hand wheel** to enhance **smooth running** and to suppress resonances.

Stepper motors are available in different configurations.

6.1 Variable Reluctance Stepper Motor

A typical example is the **variable reluctance stepper motor** featuring a stator with energizable windings and a soft magnetic iron rotor, e.g., made from electric sheet. Powering a winding pulls at the teeth closest to the magnetized pole and aligns the rotor. A fine division of the teeth achieves a high step resolution. As soon as the stator is no longer energized, the magnetic field of the soft iron rotor vanishes, i.e., it does not exhibit detent torque. For this reason, this motor type always **requires power to maintain its position**.

6.2 Permanent Magnet Stepper Motor

In a **permanent magnet stepper motor**, the stator is made of soft iron and the rotor contains permanent magnets. This design achieves **higher torques**, however, at a **lower resolution** because the rotor is difficult to make with a large number of poles.

6.3 Hybrid Stepper Motor

Nowadays, both motor variants are combined in **hybrid stepper motors** to reach a **compromise between step resolution** and **torque**. Figure 12 shows a typical design of this motor type.

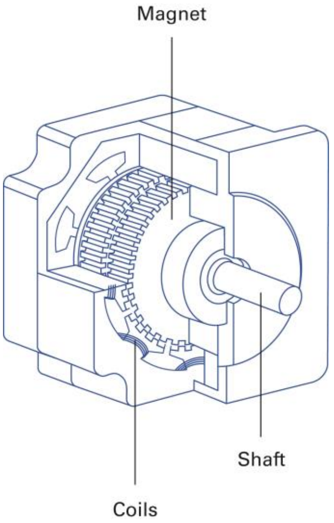


Fig. 12 Hybrid stepper motor design with a soft iron stator and toothed permanent magnet rotor.

6.4 Full-Step and Half-Step Operation

Typically, PI's 2-phase stepper motors have a step angle of 1.8 in **full-step operation**. This corresponds to 200 full steps. Full-step operation is achieved **when one phase or two phases**, respectively, **are being energized**. Energizing two phases simultaneously results in a torque increase by 30 to 40%, however, the energy consumption also doubles. Combining these two energizing variants **reduces the step angle by 50%** (**half-step operation**). The higher step resolution accounts for a **smoother** run of the motor, however, it **does not achieve the full torque** of the full-step mode with two energized phases. The torque decreases by approx. 15% which might be balanced by a higher motor current while only one phase is being energized.

Figure 13 illustrates full-step and half-step operation.

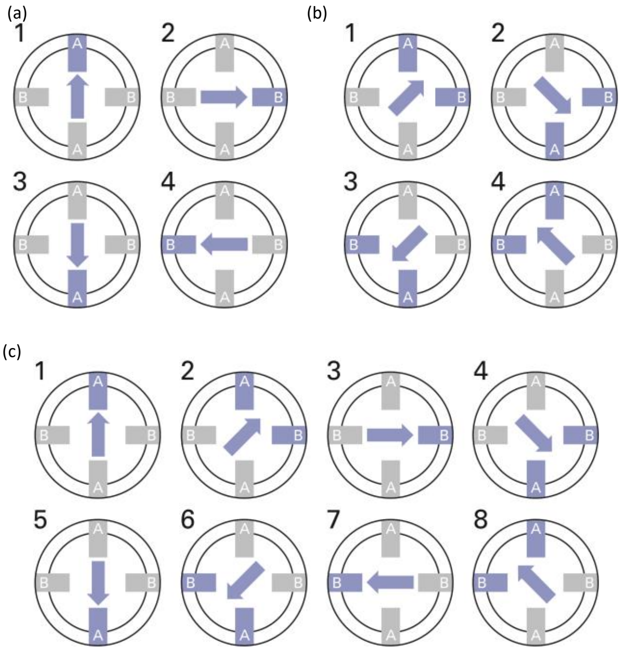


Fig. 13 (a) Full-step operation with a powered-on phase, (b) Full-step operation with two powered-on phases, and (c) half-step operation.

6.5 Microstepping Operation

The so-called **microstepping operation** achieves up to several thousand micro steps between two full steps through **electronic interpolation** and two 90° phase-shifted sinusoidal current waves. The microstepping principle is illustrated in figure 14. A **high step resolution with sinusoidal current feed** results in an **even smoother run with fewer vibrations**.

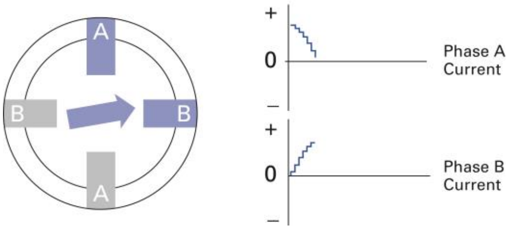


Fig. 14 Microstepping operation with a 2-phase stepper motor and with quasi-sinusoidal current progression.

6.6 Step Loss

Encoders are not mandatory because of the countable discreet step and therefore, stepper motors **can be operated in an open servo loop**. **Step losses** are possible and would result in a **positioning error**. They can occur due to **excessive**

loads and **accelerations**, or **resonance effects**. In such cases, the problems are caused by the rotor which can no longer follow the applied rotation field. However, step loss errors can only be **avoided by** closed loop operation, i.e., an **additional encoder** will be required.

Please refer to the white paper "Performance of Stepper Motor Axes" for more information on using stepper motors for precision positioning tasks.

7 Gear Motors

Gear motors are used for precision positioning tasks to provide **higher torques and higher resolutions at lower speeds**. In slow applications, the rotor moves comparably fast thanks to the gear ratio. Without gears, undesired cogging torques may occur due to the low rotor speed. Moreover, gears support the **holding forces** in **vertical applications.** Often, less effort is required for the control loop because the gear reduces the load on the motor by the square of the gear ratio.

However, a geared motor is **not play-free** and additional **friction** reduces efficiency. For this reason, gear manufacturers often offer **suitable lubrication** to guarantee the expected lifetime. The lifetime is largely subject to input speed and output torque as well as operation, ambient, and installation conditions. In customized solutions, the lifetime can be prolonged by self-lubricating bearings, ball or ceramic bearings, metal gearwheels, and special greases.

Strictly speaking, drive screws also act as gears in gear spindle positioning systems because speed adjustments are achieved on the expense of the torque in dependence of the screw pitch. To this effect, a motion platform moves twice as fast at 50% of the torque with a pitch of 2 mm/revolution compared to a pitch of 1 mm/revolution. For some applications, however, an actual gear is required to act between motor and drive screw. PI deploys various gear types for this scenario.

7.1 Worm Gears

Worm gears as shown in figure 15 consist of a shaft with helical mount and a worm wheel. The power is transferred by **sliding friction** at a right angle. For this reason, the worm shaft has **high self-locking forces**, making additional brakes in some applications unnecessary. Sliding friction however, causes a **low degree of efficiency**, **high wear**, and potentially **high temperatures**. Typically, worm gears can achieve high gear ratios at one translation level, which makes them comparatively inexpensive. PI often deploys worm gears for **rotation stages** because they transfer motion at right angles. In this way, the motor can be aligned lateral to the rotation stage.

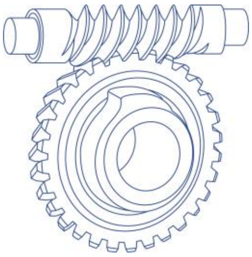


Fig. 15 Worm Gears

7.2 Bevel Gears

Bevel gears as shown in figure 16 consist of a bevel pinion and a toothed wheel with angled teeth. Similar to the worm gear, the energy is transferred at a right angle, but reaches **higher torque capacities**. High gear ratios can only be achieved with additional spur gear stages. The occurring **rolling contact** is advantageous. This makes bevel gears **low-wear and more efficient** than worm gears. However, they are often **more expensive**. PI deploys bevel gears in **customized rotation stages**.

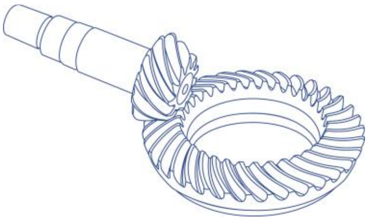


Fig. 16 Bevel Gears

7.3 Spur Gears

Spur gears as shown in figure 17 consist of two parallel but different-sized toothed wheels. Thanks to their simple structure, spur gears are **easy** to manufacture and **robust**. **All-metal models** fulfill high requirements with respect to an even and **smooth run and particularly play-free** models can be realized for applications where **high precision at low torque** is needed. To achieve this, the **preload** is set by inverse twisting of the gear trains and their tension on the motor pinion. For PI's **linear stages**, spur gears are next to planetary gears the standard choice for gear motors.

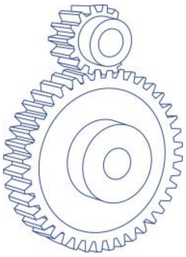


Fig. 17 Spur Gears

7.4 Planetary Gears

Figure 18 shows a planetary gear, which consists of a sun wheel connected to a shaft, and other planet wheels, which are located within a ring wheel. They are suitable for **transferring the highest torque** because **the load is distributed via several toothed wheels**. In this manner, **high gear ratios can be realized in very compact assembly spaces**. Often, the input stage's toothed wheels are made of a synthetic material to reduce high speed noises. However, for applications in vacuum, high temperatures or for very high torques, the input stage is preferably made of steel. For PI's **linear stages**, planetary gears are next to spur gears the standard choice for gear motors.

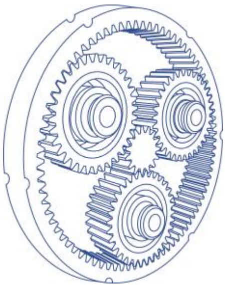


Fig. 18 Planetary Gears

7.5 Belt Gears

Belt gears, as shown in figure 19 feature double-toothed wheels connected by a belt. In this way, **larger shaft distances can be bridged** and **higher peripheral speeds** can be realized. Maintenance tasks usually involve a **belt change or restressing of the belt**. The belt **limits** the **temperature range**. The occurring **push and pull forces** usually cause **larger shaft loads**. PI often uses belt gears in **compact positioning stages**; e.g., **Z or linear stages** where the **drive is folded** on the side. Belts are suitable for vacuum **up to 10^{-6} hPa**.

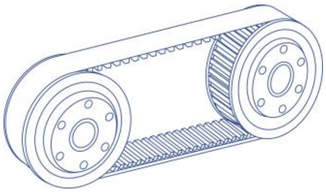


Fig. 19 Belt Gears

7.6 Harmonic Drive Gears

Harmonic drive gears, as shown in figure 20, are characterized by elasticity properties of the transmission element, allowing for **high gear ratios, high torque capacities, high linear torsional stiffness, high degrees of efficiency as well as play-free operation**. The elastic transmission element is an elliptical disc that deforms a thin steel bush with external teeth. The steel bush is located on an outer ring with ball bearing and internal teeth. When deformation occurs, the internal and external teeth interlock play-free in the area of the larger elliptical axis. Additionally, harmonic drive gears offer the possibility of using a **central hollow shaft**; e.g., for cables, shafts, or laser beams. However, these gears are comparatively **expensive** due to their **complex, compact, and maintenance-free setup**. PI sometimes uses harmonic drive gears for **customized solutions** to achieve particularly **high positioning accuracy and repeatability** thanks to the zero-play characteristic of these gears.

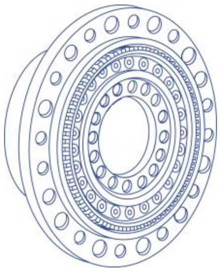


Fig. 20 Harmonic drive gears

8 Suitable Motion Controllers

PI offers **various controllers** for motors; e.g., C-863 and C-884 for DC motors, C-663 for stepper motors, C-891 for BLDC, as well as SMC Hydra, ACS or C-885 controllers with corresponding modules for all motor types.

9 Other Motor Types

PI uses further motor types like **magnetic linear** and **voice coil motors**, as well as other torque motors. PI develops these motors in-house under the name of the registered trademark **PIMag®*;*** therefore, these are being discussed in a separate white paper.

10 Summary

A variety of motorizations are available in the field of precision positioning.
Different motor types are suited for specific applications:

- **Stepper motors** are cost-efficient and suitable for vacuum applications, they offer low speed, low dynamics, and high resolution;
- **DC motors** are suitable for cost-efficient, dynamic applications;
- **ActiveDrive DC motors** offer motor performances that exceed the controller performance, and thus enable higher velocities;
- **Gear motors** provide low speed, high torque, high resolution, as well as additional holding forces in vertical applications;
- **Brushless DC motors and synchronous servo motors** are suitable for industrial applications and offer high dynamics and continuous operation;
- **Torque motors** used as direct drives for industrial applications offer high torque, zero-play, high dynamics and continuous operation, and are mainly found in rotation stages.

The characteristics and specifications of a positioning system are not only influenced by the choice of a suitable motor but also depend on a number of other factors. They also have to be considered when designing a precision positioning solution:

- Drive screw
- Guide
- Encoder model
- Encoder type
- Encoder interface
- Limit and reference point switch type
- Cable management
- Ambient conditions
- …

The following table 1 compares the most important motor characteristics. Table 2 gives an **overview** of the **motorized standard products**.

10.1 Comparison of motor types

Property	**2SM**	**DC/PWM**	**BLDC/SSVM**	**TQM**
Velocity	The velocity depends on the switching frequency. Typically, 20 to 30 revolutions/second	Proportional to the voltage, higher as with 2SM. Higher velocities with ActiveDrive. Typically, 50 revolutions/second (limited by drive screw and noise)	Proportional to the voltage, higher as with DC. Typically, 60 revolutions/second (limited by drive screw)	High velocity stability
Smooth running	Possibly vibrations at high velocity, smooth running through mechanical damper and sinusoidal commutation	Quieter than 2SM	Sinusoidal commutation for very smooth running (typical in ACS controllers, PI C-891 controller, and SMC Hydra)	
Resolution / Precision	Position information without encoder, high position stability, very high resolution in microstepping mode	Requires encoder for positioning information, resolution depends on the encoder, position jitter caused by the control loop		
Torque	Low torque in microstepping mode, high torque at low speeds	Proportional to the current		High, determined by the number of pole pairs
Self-locking	High holding force, self-locking only at a full-step (load-dependent)	Low, can only be increased by drive gear and precision drive screw		Not available
Lifetime	Higher than DC, comparable to BLDC/SSVM	Limited by brushes, typically 1,000-5,000 hours	Limited by bearings, typically several 10,000 hours, comparable with magnetic linear motors	
Miscellaneous	Less expensive than DC, long lifetime, reliable, position error at step loss	Less expensive than BLDC/SSVM, lower control effort required, high dynamics and smooth running, low heat build-up	Low maintenance, efficient and low noise, light, high reliability and dynamics, low heat build-up and few vibrations, suitable for industrial applications	Direct drive, high drive rigidity, high repeatability, high torques, play-free, hollow shaft, flat, suitable for industrial applications

10.2 Standard products overview

Type	Product family	DC	DC-G	PWM	BLDC	SSVM	TQM	2SM	2SM-G	Manual
Linear actuator (low precision)	L-402	x						x		
	M-110 / M-111 / M-112		x						x	
	L-406	x	x					x		
	L-408	x	x					x		
	VT-80	x						x		
	M-406		x	x						
	M-403		x	x						
	M-404		x	x						
	M-413		x	x						
	M-414		x	x						
	L-412					x				
	L-417					x				
	LS-180	x						x		
Linear actuator (high precision)	L-505	x	x					x	x	
	M-122.2DD1	x								
	MTS-65							x		
	M-105 / M-106									x
	L-509	x	x	x	x			x		
	L-511	x	x	x	x			x		
	M-511 / M-521 / M-531		x	x	x					
	HPS-170	x						x		
Z Stages	L-306	x						x		
	L-310	x		x	x			x		
	M-501		x	x						
	UPL-120	x						x		
XY stages	L-731	x						x		
	L-738	x						x		
	L-741	x						x		
Rotation stages	M-116		x							
	RS-40	x						x		
	DT-34		x						x	
	DT-80		x						x	

Type	**Product family**	**DC**	**DC-G**	**PWM**	**BLDC**	**SSVM**	**TQM**	**2SM**	**2SM-G**	**Manual**
	M-060 / M-061 / M-062		x	x						
	L-611	x		x	x			x		
	PRS-200		x						x	
	UPR-100						x			
	UPR-120						x			
Goniometer	WT-85	x						x		
	WT-100	x						x		
	WT-90	x						x		
	WT-120	x						x		
Linear actor (low load)	L-220		x						x	
	M-227		x							
	M-228 / M-229							x	x	
	M-230		x							
	M-232		x							
Linear actor (high load)	M-235	x	x							
	L-239	x		x	x			x		
	M-238			x						

11 Author

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12 About PI

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 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 make 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.