

Stepper motor basics

What is a stepper motor?

A stepper motor is an electromechanical system which is transducing an electrical signal into a mechanical one. It is designed to accomplish a discrete movement (notion of step) and reach a precise position.

The movement is achieved through the use of a magnetic field provided by coils and sensed by magnets. Indeed, when one of the coils is energized, a magnetic field is created and, if the energy is supplied cyclically (by means of input pulses), then the magnetic field will vary. When a magnet is placed in this varying magnetic field, it will position itself in the lowest energy state (equilibrium), therefore providing motion.

This principle is used in the stepper motor, composed of a fixed part (the stator) made of cyclically energized coils and a moving part (the rotor) made of ferromagnetic material or magnets.



Figure 1: FAULHABER stepper motor.

Why using a stepper motor?

Stepper motors do not operate as DC or brushless motors. They have no integrated electronics, no brushes and can be controlled in open loop. To get a quick idea, stepper motors are very often considered as particular brushless motor that can be controlled without feedback in open loop. Thus, even though stepper motor may look a bit more difficult to understand technically, they have the advantage of being very simple to control and need no encoder or special driver to monitor the position of the rotor.

Table 1 summarizes the differences between those 3 kinds of motor.

Table 1 : Comparison between different motor technologies. This is an estimation and can be discussed from case to case.

	Stepper Motors	DC Motors	Brushless motors
Position with feedback	Not really an option (cost)	High resolution depending on encoder	High resolution depending on encoder
Positioning w/o feedback	Good 24 steps/rev High torque	none	yes, 6 steps/rev Moderate torque
Cost (components)	Motor, 100 % Encoder 40% Driver chip, 5 % Enc.Interface. 20 % Controller 40 % Total 145% (without encoder) Total 205 % (with encoder)	Motor, 60 % Encoder 40 % Driver, 10 % Enc.Interface. 20 % Controller 40 % Total 170 %	Motor, 150 % Encoder 40 % Driver, 20 % Enc Interface 20 % Control 60 % Total 290 % (210% for BX4)
Acceleration	Good Limited to max. boost running torque	Very High Boost operation reduces brush life	Very High
Top Speed	<15'000rpm	<15'000 rpm	> 15'000 rpm
Life Time	Very good	Limited by wear of the brushes	Very good
Stability	Very high, inherent	f(Enc.res; controller)	f(Enc.res; controller)
Reliability	High (no brushes / no Hall sensors)	Low (brushes)	High (no brushes)

When using a stepper motor?

Stepper motors are suitable for applications where compact and robust solutions are required. They develop their maximum torque at stand-still which makes them naturally suitable to hold a position. The external commutation ensures that the speed is perfectly constant even if the load varies. Thanks to the absence of any electronic component, stepper motors run where the hall sensors or encoders of other type of motor find their limit: high/low temperatures, external noise disturbances, etc.

Compared to a DC motor, a stepper motor is also much easier to use for positioning application as the notion of step enables the user to know the precise position or displacement of the rotor without feedback: it runs in open loop.

Stepper motors are as a matter of fact frequently used when the following application requirements are specified:

- Repetitive positioning tasks with high accelerations (i.e. XYZ of machine tools)
- Whenever the settling time must be short and with repeatable discrete positions.
- Whenever open loop (absence of electronics) makes sense (e.g. for noise immunity).
- For back and forth motions.
- Frequent “start/stop” operation.
- Whenever the duty cycle is relatively small. (Time ON << Time OFF)
- Whenever the actual position must be held with high torque.
- Whenever the actual position must be held when no current is applied (thanks to the residual torque).
- Whenever long life times is required (i.e. using the brushless design).
- Whenever minor speed variation under load are not allowed (peristaltic pumps, XYZ of machine tools)
- For most small consumer electronic devices, such as hard disc drives, ink jet printers, cameras.

By contrast FAULHABER PRECISTEP focuses on the following market segments:

- Optical systems (e.g. zoom, focus, pan/tilt, and filter positioning, microscope stages)
- Photonics (e.g. laser tuning, laser scanner)
- Telecommunications (e.g. variable optical amplifiers (VOA))
- Medical (e.g. pumps, DNA analyzers)
- Instrumentation (e.g. gas analyzer)
- Aerospace & Aviation (e.g. Solar panel control of satellites)

Stepper motors categories and operation

There are basically three different stepper motor design types on the market:

- The permanent magnet (PM) design
- The variable reluctance design
- The hybrid design

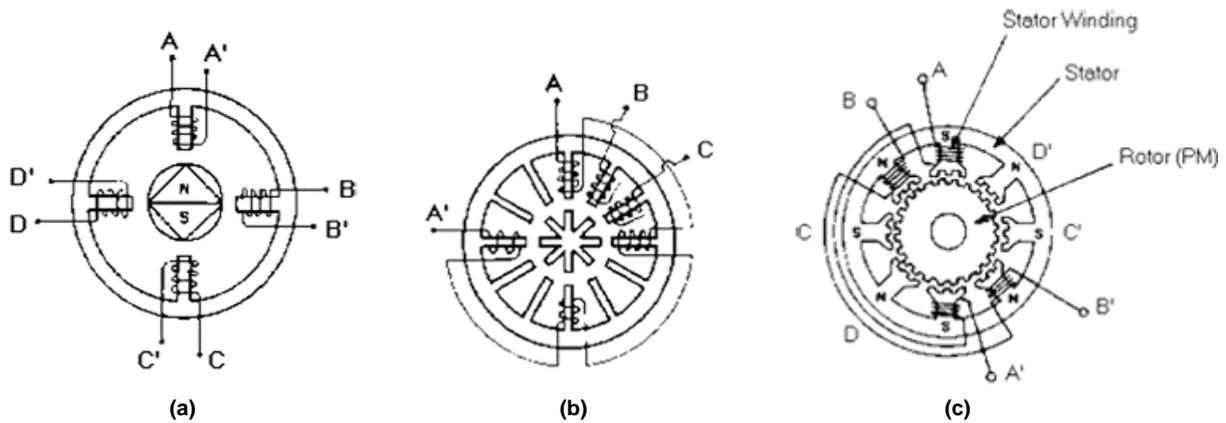


Figure 2 : (a) Permanent magnet, (b) variable reluctance and (c) hybrid stepper motors. [5]

The permanent magnet (PM) design (Figure 2a)

The rotor includes permanent magnets positioned in order to alternatively obtain South and North poles, which can interact with the varying magnetic field of the stator.

Rotation is achieved by alternatively energizing the stator coils A-B-C-D and attracting the North (or South) pole of the rotor to the magnetized stator pole. When no current is applied, a small torque is required to move the rotor from its equilibrium position due to the interaction between the permanent magnets and the stator. This is indifferently referred to as residual, detent or cogging torque in the technical literature or in manufacturers' brochures.

This design is the most popular for small stepper motors, especially below $\varnothing 20\text{mm}$, and provides high torque. The resolution is usually limited to 20 or 24 steps per revolution. FAULHABER stepper motor technology falls exclusively into this category.

The variable reluctance design (Figure 2b)

Variable reluctance stepper motors consist of a more complicated design and require an accurate manufacturing of both the stator and the rotor. The rotor, made of a ferromagnetic material (e.g. iron) has several teeth, which can be attracted to the stator poles. Once the stator coils are cyclically energized, the teeth of the rotor will be attracted and will tend to align themselves with the magnetized stator poles, thus resulting in a rotational movement. Despite the fact that higher resolutions are achieved (due to the higher number of steps per revolution), variable reluctance stepper motors provide a rather small dynamic torque. Hence, this design is not used for the smallest motors. As the rotor does not include permanent magnets, there is no risk when using this type of stepper motor in a strong external magnetic field (e.g. in MRI devices). One of the main drawback of this design apart from the low torque is that it does not hold its position when no current is applied (i.e. there is no residual torque).

The hybrid design (Figure 2c)

The concept is to have a permanently magnetized rotor with multiple teeth and a stator with multi-toothed poles, in order to combine a rotational movement by stator poles alignment and stator teeth attraction.

The hybrid design therefore combines the high torque of PM stepper motors with the higher resolution of the variable reluctance design. A very common resolution of hybrid stepper motors is 200 steps per revolution.

The manufacturing of hybrid stepper motors is technically limited to a minimum size of $\varnothing 19\text{mm}$

Physics basics

To understand the main parameters that influence the performances of the motor, it is important to have an overview of the physics behind it.

Figure 3 presents the schematic of a stepper motor represented by a torque-speed factor ($k_T\omega$), an electrical resistance (R, windings) and an inductance (L, windings). U is the applied voltage and I the current in the windings.

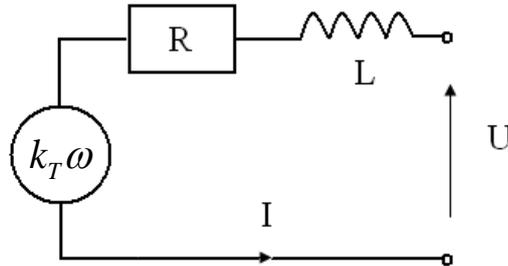


Figure 3 : Schematic of a stepper motor

The main formula expressing the behavior of the motor is given by equation 1.

$$U = RI + k_T\omega(t) + L \frac{dI}{dt} \quad (1)$$

Where

- RI = Voltage to drive current (resistance times current)
- $k_T\omega(t)$ = Voltage to compensate the back-EMF¹ (k_T is the torque constant and ω the speed)
- LdI/dt = Voltage to establish/modify current level

The torque is directly proportional to the current and can be expressed by equation 2.

$$M = k_T \cdot I \quad (2)$$

As a consequence, the current can be deduced from the previous formula as shown in equation 3.

$$I = \frac{U - k_T\omega(t) - L \frac{dI}{dt}}{R} \Rightarrow I = \frac{U}{R} \left(1 - e^{-\frac{R}{L}t} \right) - \frac{k_T\omega(t)}{R} \quad (3)$$

Figure 4 shows the current in the windings in function of time (ideal case where back EMF is null). Due to the inductance of the motor, it takes some time for the current to reach its maximum value.

¹ The back EMF is the abbreviation of back Electromotive Force. It corresponds to the voltage sensed when the rotor is moving in a changing magnetic field.

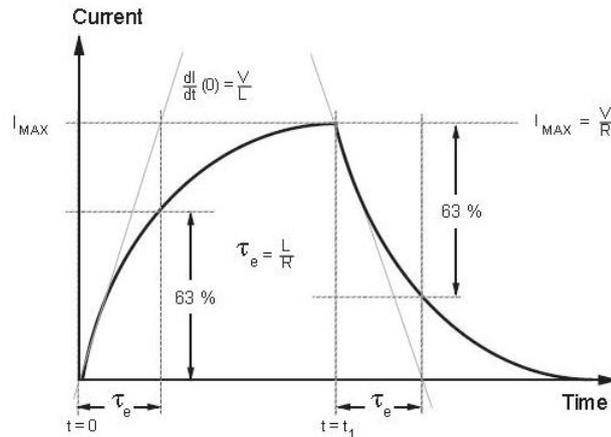


Figure 4 : Current in function of time. Current switched ON at $t=0$ and switched OFF at $t=t_1$. Note that in this case the back EMF is set to 0. At high rotational speed, the back EMF may significantly modify this behavior.

From this we can immediately conclude that the factors which influence the current, thus the torque, are:

- Inductance (L) ($L =$ winding inductance)
The inductance prevents the current to establish rapidly in the phases.
- Resistance ($R =$ winding resistance)
The resistance influences the maximal current set in the phase.
- The back EMF
When the speed ω increases, the back-EMF proportional to $k_T\omega$ increases and the current decreases, hence the torque decreases. This explains why we observe on the torque/speed curves of the data sheet that the torque declines when speed increases whatever the operation mode of the motor.

How does a stepper motor rotate?

From now on, we will concentrate on permanent magnet stepper motors, which are the ones designed and manufactured by FAULHABER.

Figure 5 shows a simplified schematic of the operation for a two-phase permanent magnet stepper motor and Figure 6 the corresponding energizing sequence of the coils (clockwise rotation). For a counter-clockwise rotation, the sequence must be reversed.

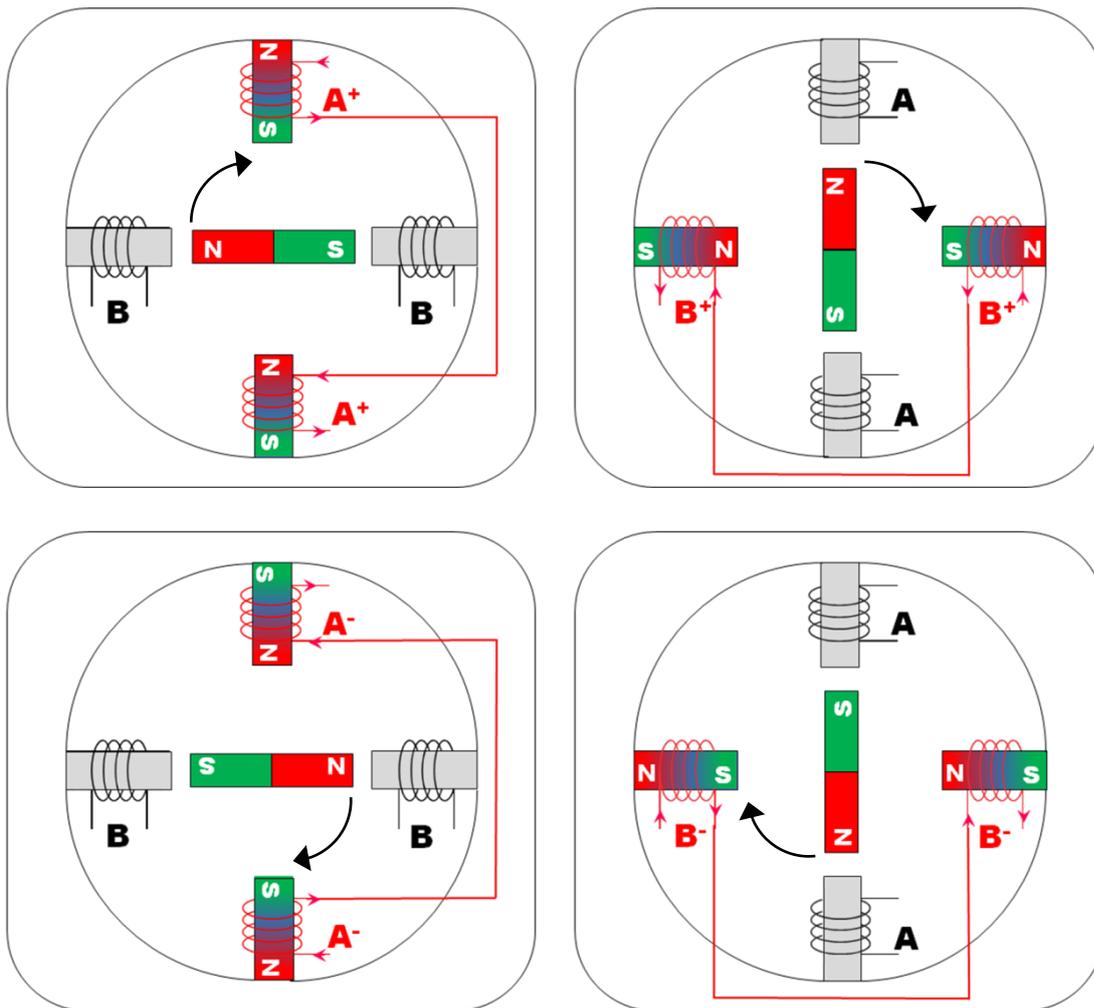


Figure 5 : Operation of a permanent magnet stepper motor ("one phase-on" configuration).

Step	Phase A		Phase B	
	Pin 1	Pin 2	Pin 3	Pin 4
1	+	-		
2			+	-
3	-	+		
4			-	+

Figure 6 : Energizing sequence of permanent magnet stepper motor ("one phase-on" configuration).

As one coil is energized, a magnetic field is created and attracts the North or South pole of the magnet, depending on the polarity of the energized coil. By alternatively energizing the different coils (giving birth to a sequence), it is then possible to rotate the magnet

Phase, poles and step angle

Usually, stepper motors have 2 phases, but some of them may also have 3 or 5 phases.

Bipolar stepper motors usually use one winding per phase because the current in the winding can be made to circulate in both directions. Unipolar stepper motors use one winding per phase with a tap in the middle; hence, half of the winding is used for positive current flow and half for negative current flow (corresponding to two separate coils). FAULHABER PRECISTEP designs and manufactures only bipolar stepper motors.

A pole is defined as a region where the magnetic flux density is concentrated. It corresponds to the North or the South “pole” of a magnet. FAULHABER stepper motors feature between 10 and 100 poles (corresponding to 5 to 50 pole pairs) in combination with 2 phases, which leads to 20 to 200 steps per revolution.

The step angle is determined by the number of steps, for instance a stepper motor with 20 steps will define a step angle of $18^\circ (=360^\circ/20)$

$$\text{Step angle} = \frac{360}{N_{ph} \cdot Ph} = \frac{360}{N} \quad (4)$$

Where

- N_{ph} = number of equivalent poles per phase = number of rotor poles
- Ph = number of phases
- N = total number of poles for all phases together

One phase-on and Two phase-on

There are two main ways to energize a stepper motor (when operating in full steps). Either 1 phase is energized at a time (“1 phase-ON” configuration) or 2 phases are energized at the same time (“2 phase-ON” configuration). For the “1 phase-ON” configuration, the commutation sequence is $A+ \Rightarrow B+ \Rightarrow A- \Rightarrow B-$ for a direction and $A+ \Rightarrow B- \Rightarrow A- \Rightarrow B+$ for the opposite rotation direction. For the “2 phase-ON” configuration, the sequence is $A+B+ \Rightarrow A-B+ \Rightarrow A-B- \Rightarrow A+B-$ for one direction of rotation and $A+B+ \Rightarrow A+B- \Rightarrow A-B- \Rightarrow A-B+$ for the other direction.

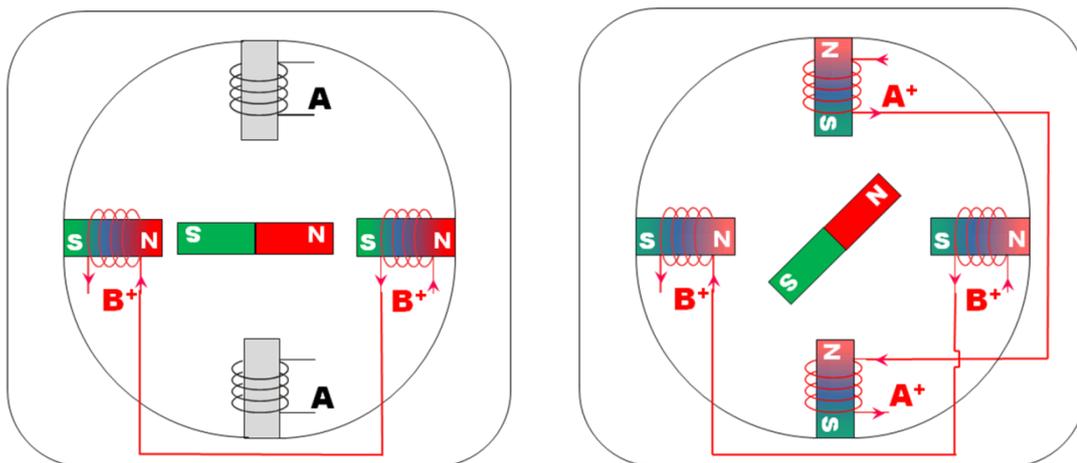


Figure 7 : Position of the rotor during (left) “1 phase-ON” and (right) “2 phase-ON” operation.

The evolution across time of both phase current signals for each type of configuration is different, as illustrated in Figure 8. The clock pulse signal (green), corresponding to the commutation speed, determines the rotation speed of the rotor. If the same torque of both “1 phase-ON” and “2 phase-ON” configurations is required, then the current applied in the “1 phase-ON” configuration must be $\sqrt{2}$ times higher than the current applied in the “2 phase-ON” configuration (same power consumption).

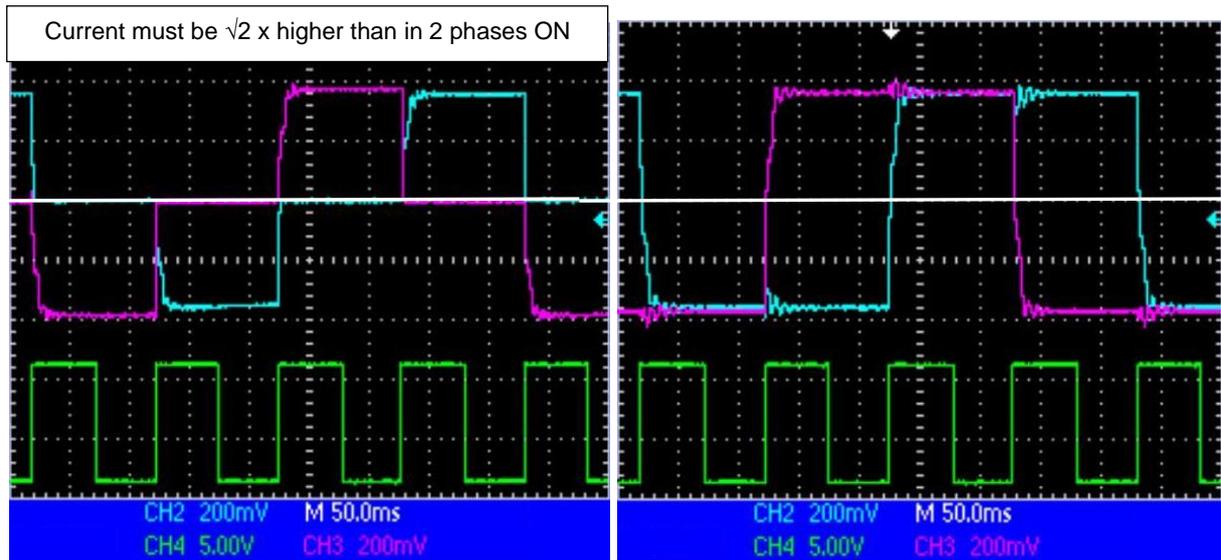


Figure 8 : Evolution of phase current signals (lilas for phase A; light blue for phase B) for (left) "1 phase ON" configuration and (right) "2 phase-ON" configuration operation. The clock pulse (green signal) determines the rotation speed.

To understand why the current must be $\sqrt{2}$ times higher in 1 phase-ON operation to obtain the same torque than in 2 phase-ON operation, Figure 9 below can help :

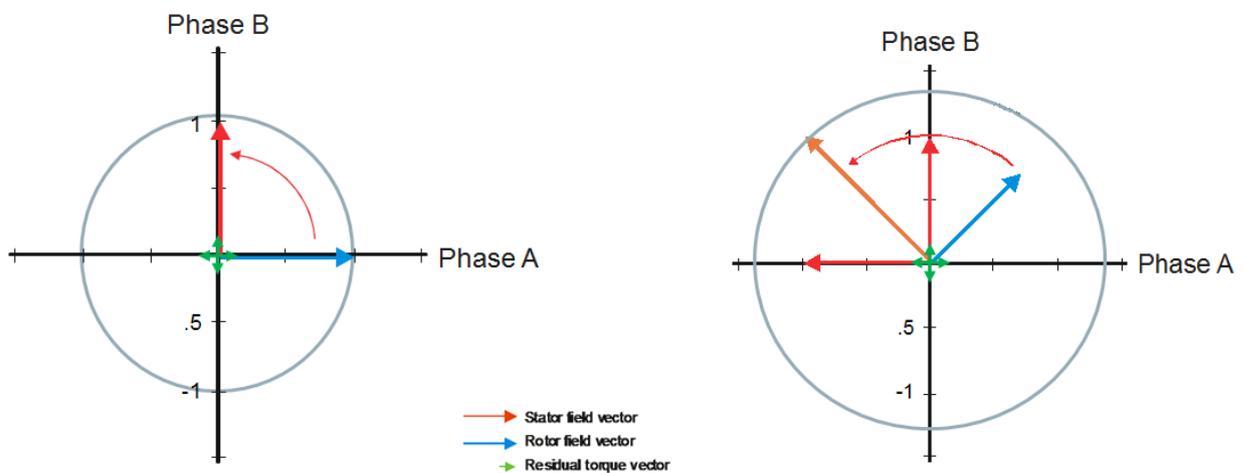


Figure 9 : (left) 1 phase-ON vectorial representation and (right) 2 phase-ON vectorial representation.

When 2 phases are energized at a time, the sum of the vector equals $\sqrt{2}$ times the separate value of one phase, which explains why the current in 1 phase-ON must be higher to obtain the same torque at the output.

Full-stepping and half-stepping

When alternating both "1 phase-ON" and "2 phase-ON" operations, the rotor can achieve half-steps. The commutation sequence is thus given by $A+ \Rightarrow A+B+ \Rightarrow B+ \Rightarrow B+A- \Rightarrow A- \Rightarrow A-B- \Rightarrow B- \Rightarrow B-A+$, which is twice the number of steps obtained with full-step operation, the step angle also being halved. For counter-clockwise rotation, the sequence is just reversed. If the same torque between each half step is required, then the current applied in the "1 phase-ON" configuration must be $\sqrt{2}$ times higher than the current applied in the "2 phase-ON" configuration (see paragraph 1.8).

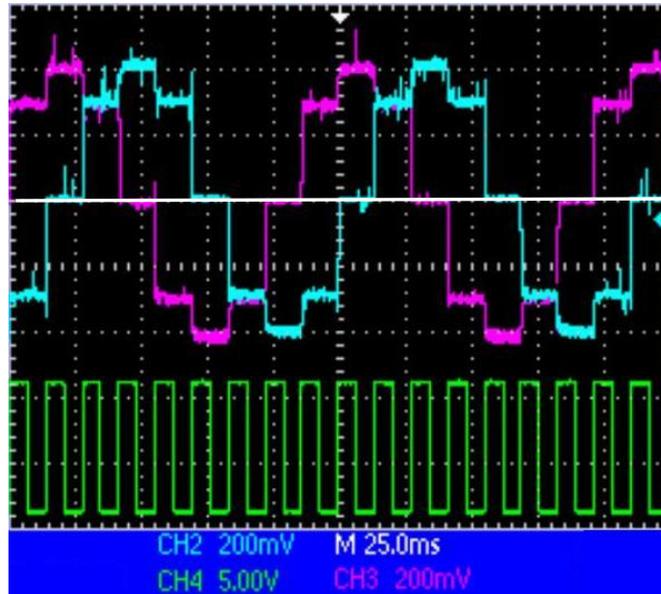


Figure 10 : Evolution of phase current signals (lilas for phase A; light blue for phase B) for half-stepping operation, with phase current compensation.

Micro stepping

For operation at low speed (typically below 600 rpm) or if a resolution of less than a half-step is required, micro stepping is the ultimate solution. By properly energizing the windings, it is possible to move the rotor less than a degree. Most drivers can support such an operating mode .The idea is to energize two coils in such a way, that the rotor will position itself according to a smaller step angle. By extension, supplying each phase current in form of a sine wave allows the stepper motor to achieve a very high degree of resolution. Such an operating mode is explained in more detail in the separate micro stepping application note (AN015).

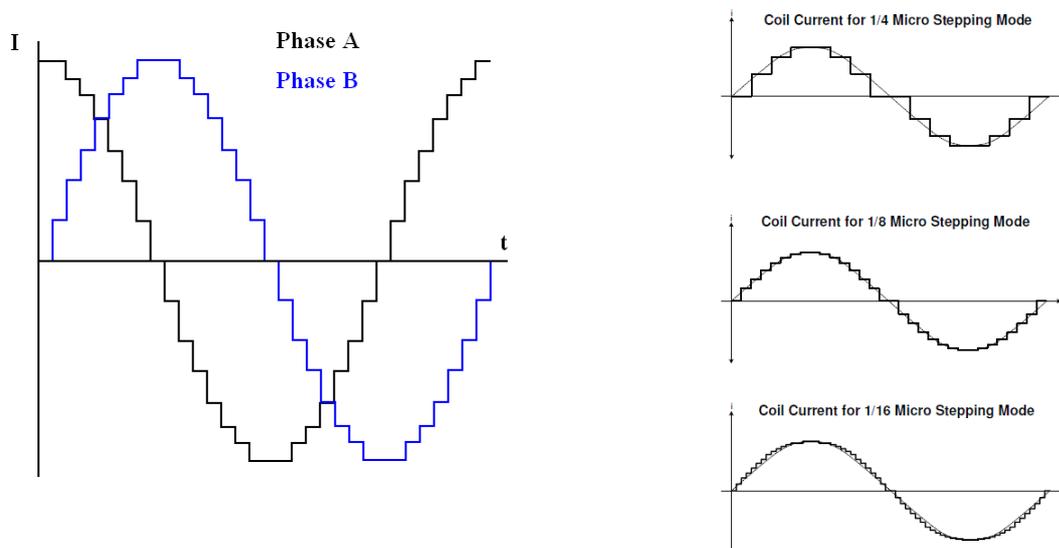


Figure 11 : (left) Phases current for micro stepping operation (8 microsteps/step in this case). (right) Shape of the signal for one phase at different micro stepping modes. The current signal tends to be sinusoidal. [6]

FAULHABER Technology

FAULHABER technology contains two basic stepper motor designs, which can be easily identified by their “AM” and “DM” model designations. Both are 2 phase stepper motors using permanent magnets. The AM stepper motor product line contains 2 windings (one for each phase) and the DM line contains 4 windings (two for each phase). The AM design uses a radial magnetic field for the actuation of the rotor (“M” for Magnet), whilst the DM design uses an axial field with a disk magnet (“DM” for Disc Magnet).

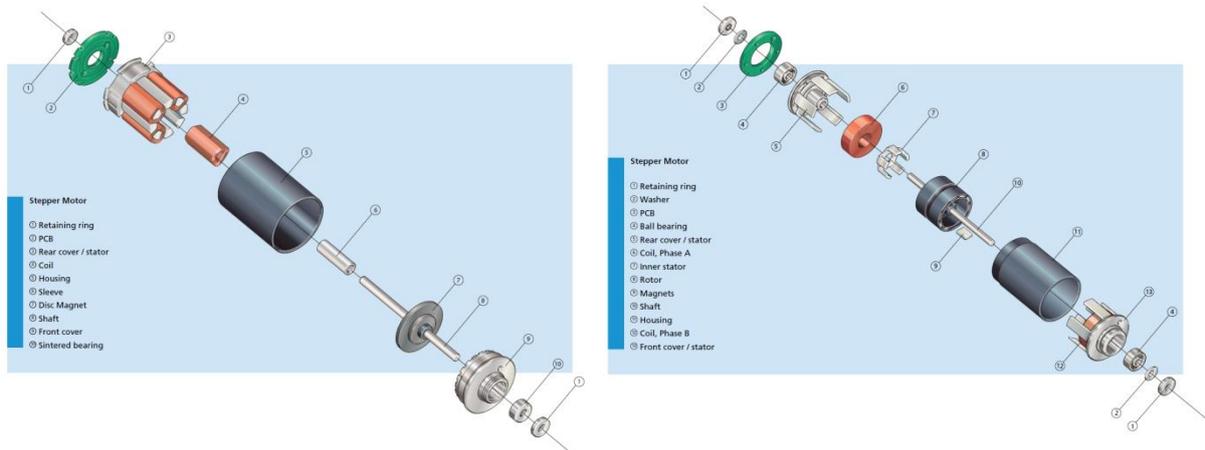


Figure 12 : FAULHABER DM (left) and AM (right) stepper motor designs.

Benefits of the disc magnet stepper motor design:

- Low inertia
- High angular accuracy
- High acceleration
- Lower residual torque

Benefits of the reported magnets stepper motor design:

- High torque/volume ratio
- Robust and simple construction

Custom solutions

Thanks to its Research and Development department, FAULHABER PRECISTEP is able to offer custom solutions. Those range from a special labeling on the motor to a complete motor with a filter wheel on its shaft.



Figure 13 : Two examples of custom solutions realized at FAULHABER PRECISTEP.

Successful FAULHABER stepper motor applications

FAULHABER stepper motors are predominantly sold for medical and optical applications, but it is truly not confined to those two market segments. The idea of this section is to present some successful applications realized with FAULHABER stepper motors.

Drug delivery pump (medical application)

The battery powered drug delivery pump (e. g. insulin pumps used against diabetes or pain treatment pumps) application field is growing of interest. Therefore, many medical manufacturers try to design and develop their own pump. In such devices, a motor is usually used to rotate or position a piston that controls the injection of the drug. The motor operates infrequently (time ON \ll time OFF), must hold the position without current and move the piston at a very steady speed. Together with the requirement for a simple and compact electronic, the stepper motor truly makes sense.

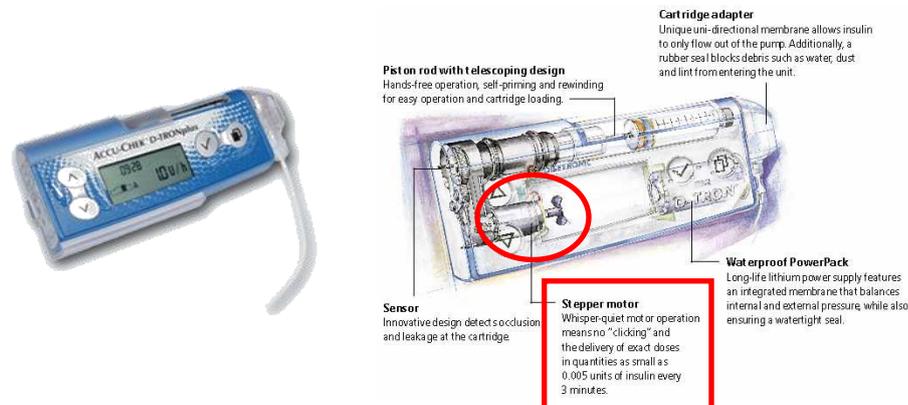


Figure 14 : Insulin pump with a schematic representation of the internal design using the stepper motor.

Hand-held X-ray analyzer (instrumentation application)

The hand-held X-ray analyzer enables to scan a metal object and characterize its composition. The role of the stepper motor is to position a metal filter wheel in order to calibrate the device. The very short length of the stepper motor and its easy to integrate control electronic are appreciated by the manufacturers of such equipment.



Figure 15 : Hand-held X-ray analyzer (left) and an example of filter wheel integrating a stepper motor (right).

X-Y microscope stage (optical application)

Stepper motors are also widely used in optical elements, which are often integrated in other applications (medical, instrumentation, etc.). In this example, the stepper motor is used to move a microscope stage. Again, the stepper motor naturally makes sense since it's a compact drive and the open loop control cannot be faulted since the operator of the microscope visually actually control the position.



Figure 16 : Picture of microscope stage

Gyroscopic camera (Aviation application)

Unmanned planes, also known as drones, need cameras with high stability and image precision. Hence, the integration of stepper motors in such systems to control either the zoom /focus of the image or the pan/tilt of the camera.



Figure 17 : Unmanned observation plane (left), with a closer view of the camera system (right).

Product codification

The correct code for ordering a FAULHABER stepper motor is illustrated below for an AM1524 motor:

AM15242R025007	Complete motor designation
AM15242R025007	Design type
AM15242R025007	Diameter in mm
AM15242R025007	Number of steps per revolution
AM15242R025007	Bearing/lubricant type
AM15242R025007	Winding type
AM15242R025007	Execution (shaft, pinion, PCB, etc.)

FAULHABER PRECISTEP also offers drivers, lead screws with nut and bearing, special lubricants, gear-head solutions and cables.

References

- [1] S. Motor, D. Considerations, and C. Problems, "APPLICATION NOTE STEPPER MOTOR DRIVER CONSIDERATIONS," no. December 2003, pp. 1–11.
- [2] "Lead Screw Efficiency." [Online]. Available: http://www.askitd.co.jp/eng/technical_info/feed_screw. [Accessed: 19-Jun-2013].
- [3] "Better Soldering." [Online]. Available: http://www.elexp.com/t_solder.htm. [Accessed: 20-Jun-2013].
- [4] "Eddy Currents." [Online]. Available: http://en.wikipedia.org/wiki/Eddy_current. [Accessed: 20-Jun-2013].
- [5] "Stepper motor types." [Online]. Available: www.anaheimautomation.com. [Accessed: 18-Jun-2013].
- [6] Trinamic, "TMC223 Datasheet." [Online]. Available: http://www.trinamic.com/tmctechlibcd/integrated_circuits/TMC223/TMC223_datasheet.pdf. [Accessed: 18-Jun-2013].
- [7] "The right and wrong of soldering." [Online]. Available: http://karma-laboratory.com/petridish/2005/01/the_right_and_w.html. [Accessed: 20-Jun-2013].

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