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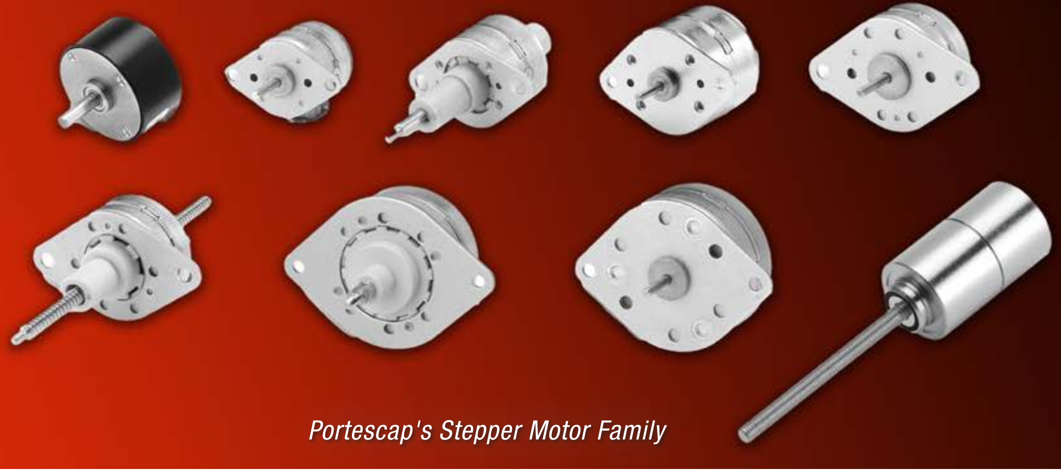
WHITE PAPER

A GUIDE TO STEPPER MOTOR TERMINOLOGY AND PARAMETERS



Portescap's Stepper Motor Family

The operation of stepper motors is less intuitive than the operation of either brush DC or brushless DC motors. As a result, they are often perceived as more difficult to understand and control. However, stepper motors are positioning devices by nature, enabling the design of simpler, less complex, and more compact motion systems for applications in the medical and life sciences fields, among others. We aim to facilitate this understanding by providing a brief overview of stepper motor technology and terminology, especially in relation to catalog research.

AN INTRODUCTION TO STEPPER MOTORS

Stepper Motors Explained

Stepper motors convert electrical pulses from the electronic drive to discrete mechanical steps, or angular steps for a rotary stepper motor. They are similar to synchronous brushless motors in that they feature a brushless design where the phases of the motor are electronically commuted with the help of a drive. This contrasts with brush DC motors, which are characterized by a mechanical commutation system that is completed by the mechanical contact of the brushes against collectors.

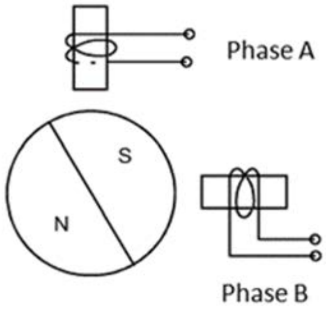


Figure 1. The simplest permanent magnet stepper motor representation is a one pole-pair magnet on the rotor and two phases on the stator. The total number of full steps per revolution for this simple motor is equal to 2 poles x 2 phases = 4 steps.

The architecture of stepper motors is quite similar to BLDC motors, especially in regard to the motor's rotor and stator:

1. **Motor Rotor.** The rotor is either made of a ferromagnetic toothed part (i.e. without a magnet), making it a variable reluctance stepper motor, or the rotor holds permanent magnets, making it a permanent magnet stepper motor. The magnets usually have many pole pairs to ensure high step resolution.

2. **Motor Stator.** The stator is composed of the coil windings of the phases, though it differs by the number of phases compared to a brushless motor. A typical permanent magnet stepper motor has 2 phases, whereas a typical brushless motor has 3 phases. These are the most-encountered motor types on the market, but it is possible to design brushless or stepper motors with a different number of phases. Note that variable reluctance stepper motors have at least 3 phases; otherwise, the direction of rotation would be uncertain. Portescap's can stack stepper and disc magnet stepper motors are both permanent magnet steppers and therefore have a 2-phase design.

Most of the time, a stepper motor is driven in open loop by applying the current in the phases independently of the rotor position. The rotor will stay locked at a given position as long as the current is maintained in the phases and does not change. For an application requiring incremental angular motion, it is very convenient to use a stepper motor in open loop. In this case, the motor does not require any feedback system (like an encoder) in order to know the rotor position. The position of the rotor is known directly based on the number of steps asked by the electronic. However, it is critical to know the load applied on the motor precisely to ensure the motor is powerful enough and prevent stalling and losing steps.

Note: Adding an encoder to a stepper motor makes it possible to drive the motor in closed loop like a brushless servomotor. By doing so, it is possible to get the most performance out of the motor. However, this setup is a more complex and costly system because of the addition of an encoder and the use of a more advanced electronic drive.

Stepper Motor Technology and Applications

There are three main stepper motor technologies in the Portescap product portfolio: can stack stepper motors, linear actuator stepper motors, and disc magnet stepper motors.

1. **Can Stack Stepper Motors.** Can stack stepper motors are generally offered when reasonable accuracy and moderate torque are required. This permanent magnet stepper motor utilizes the simplest of techniques and designs to create an effective solution; typical applications utilizing this technology include clinical diagnostics and valves or antenna positioning.

2. **Linear Actuator Stepper Motors.** Linear actuator stepper motors create translational motion with the simple operation of a can stack motor, resulting in a cost-effective and reliable motion solution. The available captive design reduces overall size and produces purely translational motion while the non-captive linear stepper design provides a longer travel stroke. Common applications utilizing linear actuators in the medical field vary from a syringe pump and electronic pipettes to different translations of components in point of care devices. This technology is also used in HVAC valves, industrial automation for adjustment mechanisms, and antenna positioning in the telecommunication field.

3. **Disc Magnet Stepper Motors.** Disc magnet steppers feature a unique design characterized by a thin magnet disk. This enables finer step resolutions than permanent magnet stepper motors in a given envelope, significantly higher acceleration due to low inertia, and greater top speed than conventional steppers due to a shorter magnetic circuit presenting lower iron losses. Therefore, these stepper motors are ideal in applications that require fast incremental motion and excel in applications that require both the motion precision of a stepper motor and the speed and acceleration of a brushless DC motor; they are also well-suited for mobile applications, devices with size limitations, and applications requiring fast and precise positioning.

   Typical applications in the medical field utilizing these motors are electronic pipettes and drug delivery systems like insulin pumps, as the motor allows dispensing of the targeted volume exactly and with excellent repeatability. They are employed for pick and place applications in the semiconductor industry, as the motor allows high dynamic and great accuracy for optimal productivity; optical lens positioning also uses disc magnet motors because they are very compact and provide high resolution and good dynamics to position lenses. This motor technology is also used in the textile industry for yarn guides, both in open and closed loop operation, as it allows extremely high dynamic to move the yarn guide back and forth.

Stepper Motor Terminology

Understanding the terminology surrounding stepper motors is critical to having a robust working knowledge of this motor technology. Some of the parameters are common between different motor technologies, such as electrical parameters (resistance, inductance, rated current), thermal parameters, or inertia. However, there are many other characteristics, like step per revolution, that are wholly specific to stepper motors.

Note: Specific parameters related to stepper motors' performance in static mode and in dynamic mode are provided in the Portescap catalog to assist in making the right selection.

Intrinsic Parameters

These parameters help to assess whether the design characteristics of the motor are compatible with the application performance or how they will impact the application performance.

1. **Steps per Revolution.** This is the number of full steps the motor can do over one full revolution. This also corresponds to the number of stable positions the rotor can reach when driving the motor in full step mode. It can be calculated from the number of pole pairs and the number of phases: steps per revolution = number of phases x number of pole pairs.

2. **Step Angle.** This is the angular rotation during one full step, generally given in degrees. It can be calculated from the number of steps per revolution: step angle = 360° / Steps per revolution.

3. **Rotor Inertia.** This is the inertia of the rotor in kilogram x meter square [kg.m^2].

Electrical Parameters

These parameters are useful to select the driver and set the electronic parameter properly for the instance.

4. **Resistance per phase, typ.** Coil winding electrical resistance in Ohm [Ω]. This parameter depends on the length and the diameter of the magnet wire used to wind one phase coil.

5. **Inductance per phase, typ.** Coil winding electrical inductance in mili-Henry [mH]. This depends mainly on the magnetic circuit and is proportional to the square of the number of turns of the coil. It is generally measured at a frequency of 1kHz.

6. **Electrical Time Constant.** This is the time constant L/R (inductance divided by resistance) in second [s], which characterizes the 1st order exponential raise of the current in the motor phase.

   This parameter is important for stepper motors, as it plays a significant role in motor performance at high speed. Since steppers have a high number of magnetic poles, the commutation frequency is high; therefore, the time step to let the current rise in the phase will become too small to allow the current to establish fully up to its maximum value U/R.

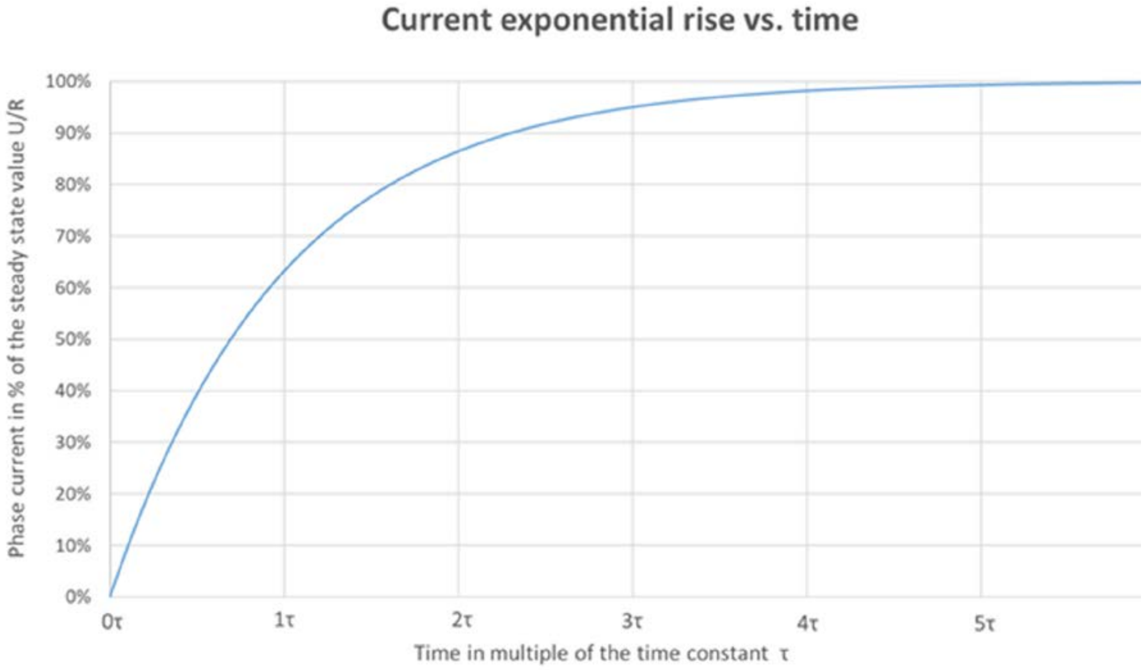


Figure 2. Current exponential rise vs. time when applying a voltage step U to the motor phase.

7. **Operating Voltage.** Also called the nominal voltage in Volt [V], the operating voltage generally provides an indication for driving the motor with a voltage drive. This is the maximum voltage that can be applied to one phase of the motor to reach the rated current of the motor. We can use Ohm's law to verify this relationship knowing the phase resistance: U = R x I.

8. **Nominal Phase Current (2 ph. On) and Nominal Phase Current (1 ph. On).** This is the maximum current in Ampere [A] which can be supplied continuously to the motor. Usually, the current value is limited by thermal constraints. The maximum Joule losses the motor can accept are equal to $\Delta T/R_{th}$.

   Here is an example where:

   - $R_{th} = 50°C/W$ and $\Delta T = 100°C$, so $P_{joules} = 100/50=2W$
   - The phase resistance of the motor is $R = 1\Omega$

   In full step 1 phase on:

   $$P_{joule} = R * I_{1\varphi ON}^2 \text{ and } I_{1\varphi ON} = \sqrt{\frac{P_{joule}}{R}} = \sqrt{\frac{2}{1}} = 1.41A$$

   However, in full step 2 phase on:

   $$P_{joule} = 2 * R * I_{2\varphi ON}^2 \text{ and } I_{2\varphi ON} = \sqrt{\frac{P_{joule}}{2*R}} = \sqrt{\frac{2}{2}} = 1A$$

   We can now see that: $\boxed{I_{2\varphi ON} = \frac{I_{1\varphi ON}}{\sqrt{2}}}$

Thermal Parameters

The thermal parameters help to understand the thermal limitations and validate that the motor can be operated safely without overheating.

9. **Maximum Coil Temperature.** This is the maximum temperature in degrees Celsius [°C] that the coil can support without damage. Exceeding this limit could burn the coil and would cause irreversible damage.
10. **Thermal Resistance Coil-Ambient.** This is the thermal resistance in degrees Celsius per Watt [°C/W] between the coil and the ambient air around the motor, considering the motor hanging in the air. This value reflects the ability of the motor to dissipate heat to the ambient air and will reduce in case an of active cooling (heat sink, fan). Coupling the motor to a metallic part will also reduce the motor's thermal resistance.
11. **Ambient Temperature Range.** The range of the environmental temperature, in degrees Celsius [°C], at which the motor can operate safely. Note that when operating the motor at a temperature higher than 25°C, the current needs to be adjusted to prevent overheating of the coil.

Motor Performance in Static Mode

Stepper motors can be used as positioning devices. This section will explain how the motor performs in such conditions and the main parameters to consider.

12. **Holding Torque, Nominal Current.** This is the maximum static torque in Newton.meter [N.m] generated by the motor when energized at a nominal current. Practically, this torque can be measured by energizing one phase at the rated current and by loading the motor progressively until it loses the step; it can also be completed by energizing both phases using the 2-phase On rated current. The maximum load torque reached corresponds to the holding torque of the motor.

    When applying more than the nominal current, a duty cycle must be applied to keep the coil temperature below the maximum rating. Saturation happens when the ferromagnetic material cannot conduct more field despite increasing the current and means that above a certain level of phase current, the torque generated by the motor will not increase proportionally to the current any longer. However, the Joule losses generated in the coil will increase proportionally to the square of the current: P_{Joule} = R x I ^2.

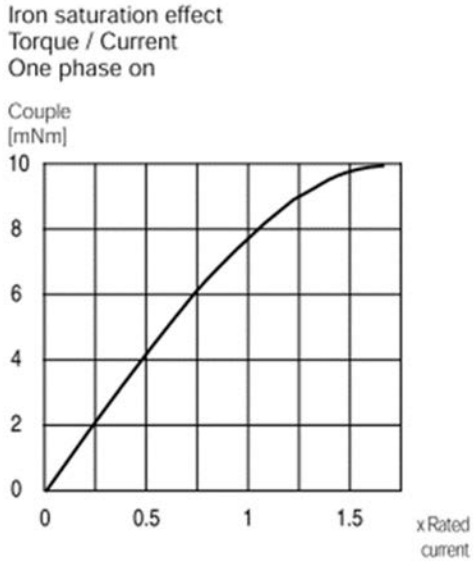


Figure 3. Torque Saturation Curve of a P110 064 Motor.

For some motors, the holding torque can also be given at 1.5 rated current to appreciate the saturation of the magnetic circuit and the capability to "boost" the motor. From the holding torque value, we can define the motor torque constant with the following formula: Kt = $T_{holding}$ / I_{rated}. The torque constant is not usually defined for stepper motors because the holding torque is not a torque that is supposed to be reached.

Even if we do not speak about torque constant, the back-EMF is indicated in many catalogs. The torque constant can be derived from the Back-EMF with the following formula: Kt [Nm/A] = Back-EMF [V/rpm] * PI / 30.

13. **Back EMF Amplitude.** The back-EMF amplitude is the amplitude 0-peak in Volt that can be measured at one phase of the motor, when the motor is back-driven at a given speed/step frequency (Figure 4).

    This is given in Volt / 1000 steps / second [V/kstep/s]. It can be converted in V/krpm with the following formula: Back-EMF [V/krpm] = Back-EMF [V/kstep/s] * 2 * 2 * N / 60, where N = number of pole pairs.

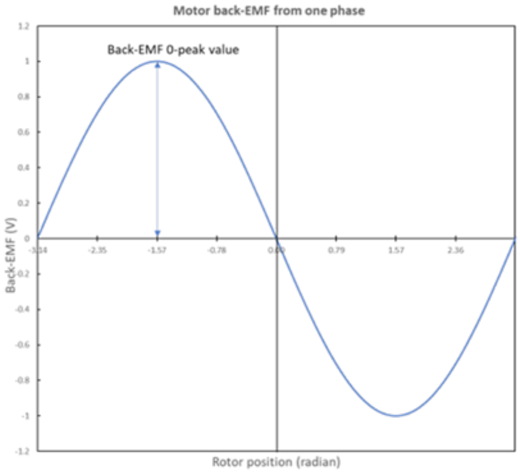


Figure 4. Back EMF Amplitude in a Stepper Motor.

14. **Detent Torque.** Also called residual torque, it is given in Newton.meter [N.m]. The detent torque indicated in catalogs is usually a combination of the residual torque due to the magnetic circuit and the friction torque (friction from the sleeve bearings or the ball bearings). The detent torque without friction is typically due to the attraction of the magnetic poles of the rotor in front of the slots of the stator when the motor is unenergized. It is a 4th harmonic of the torque generated by one of the motor phases.

    Detent torque can be useful to hold position without energizing the motor, which can save on power consumption. On the other hand, detent torque will create distortion of the total available torque, which is not desirable when driving in microstep.

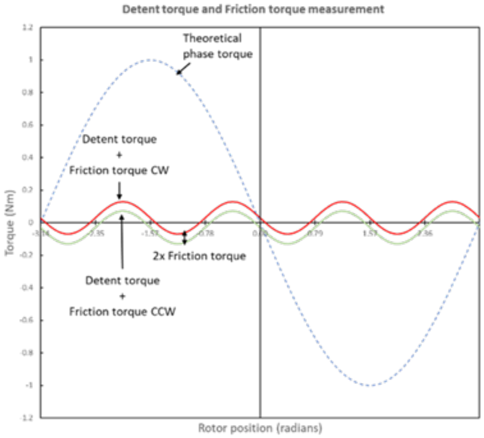


Figure 5. Detent Torque and Friction Torque Measurement.

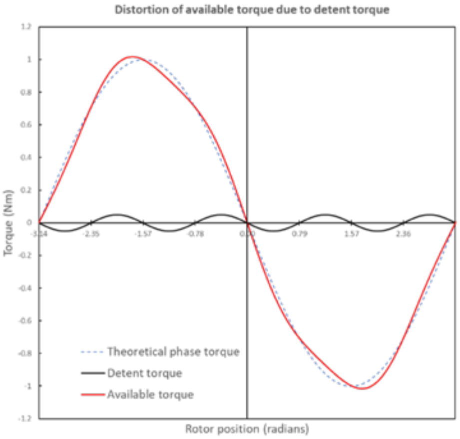


Figure 6: Distortion of Available Torque Due to Detent Torque.

15. **Stepper Motor Working Point and Load Angle.** In this example, the friction torque of the motor is neglected. At no-load the motor will not generate any torque as the electric angle between the rotor magnetic field and the stator magnetic field is 0°. The maximum torque, also called the holding torque, will be generated when the angle between these two fields is equal to 90°. When loading the motor, it will reach an equilibrium position where $T_{motor} = T_{load}$.

The load angle between the equilibrium position of the rotor under load and the theoretical equilibrium position of the rotor at no-load will be equal to:

$$\Delta\theta_{equilibrium} = arcin\left(\frac{T_{holding}}{T_{load}}\right) \text{ (in electrical degree)}$$

For a motor with N pole-pairs, the mechanical angle will be equal to:

$$\beta = \frac{\Delta\theta_{equilibrium}}{N}$$

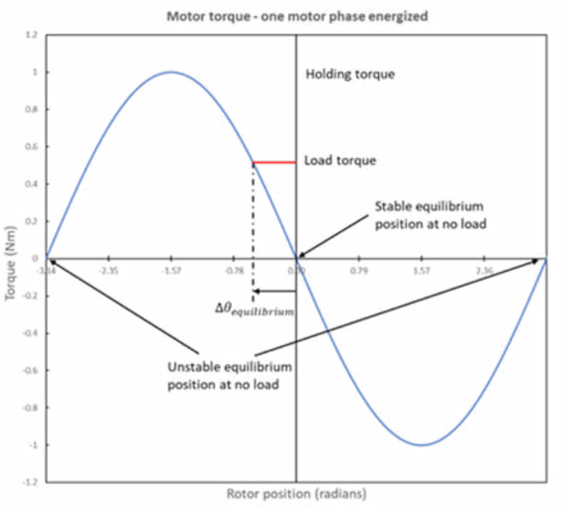


Figure 7. Working Point of Stepper Motor in Static Mode.

16. **Absolute Accuracy 2 ph. On, Full Step Mode.** This is the maximum possible angular deviation per full step, from the theoretical step angle value, when the motor is energized 2-Phase On. It is given in percentage [%] of the full step angle. The accuracy depends on multiple parameters, such as friction, torque distortion due to detent torque, saturation, or mechanical part tolerances. This error is non-cumulative.

Motor Performance in Dynamic Mode

It is not as easy as with other motor technologies to determine the torque of the motor in dynamic conditions at a given speed by literal calculation. As mentioned earlier, when operating the motor in open loop (i.e. pulses are sent to the drive, with one pulse meaning one step or one micro-step to move), the pulse frequency will represent the motor speed and our assumption is that the rotor will execute the motion. To ensure that our assumption is correct, we must be sure that the load torque does not exceed limitations. For that matter, pull in and pull-out torque curves are generally provided for every stepper motor. Note that these curves are always defined for one motor and for one specific driver, as the driver characteristics will impact the performance of the motor.

17. **Pull-Out Torque.** The pull-out torque, or dynamic torque, is the maximum torque the motor can deliver at a given speed. Since it is not possible to easily calculate the motor performance at a given torque and speed, Portescap provides a curve showing the maximum dynamic torque vs. speed. To measure it, we first reach the speed without any load by increasing the step frequency. Then the motor is loaded until it loses the synchronism. A good rule of thumb is to consider a safety margin of 30% based on the maximum load torque of the application. Please note that this pull-out torque curve will depend on the type of driver used.

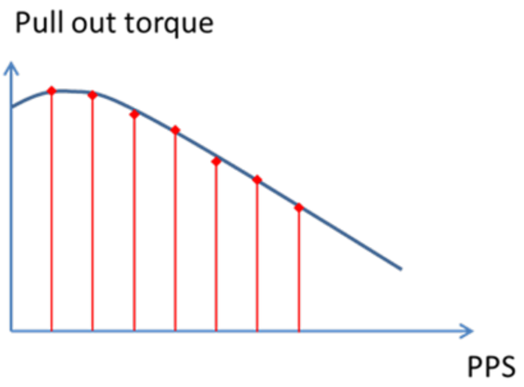


Figure 8. Pull Out Torque Curve. The red line and points illustrate how it builds by iterative practical measurements.

18. **Pull-In Torque.** The pull-in torque is the maximum torque load that can be applied to the motor when starting at a given step frequency. Unlike pull-out torque, there is no acceleration ramp generated to reach the desired speed. To measure pull-in torque:

    a. The motor is locked at one position.
    b. A load is applied to the motor.
    c. We try to start at different speeds by generating constant pulse frequency (no ramping).
    d. The highest speed at which the motor can start will be the value selected the build the curve.

    The pull-in torque will depend on the drive used, and a good rule of thumb is to consider is a safety margin of 30%.

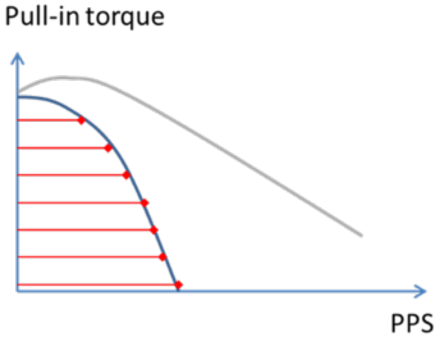


Figure 9. Pull In Torque Curve. The red line and points illustrate how it builds by iterative practical measurements.

19. **Natural Resonance Frequency.** This corresponds to the full step frequency in step per seconds or Herz [Hz] at which the motor will be subject to instability due to the resonance phenomenon. After each step, the rotor oscillates and stabilizes at the target angular position by oscillating at its natural frequency. Operating the motor at the resonance frequency can result in losing steps or even going backward. There are a few options to avoid motor resonance:

    - Try not to work in this frequency; it's sometimes easy to start at a higher frequency.
    - If the motor passes through the fundamental resonance frequency, we can reduce or increase the current to change the frequency.
    - Driving the motor in micro steps will allow smoother operation by reducing the amplitude of the oscillations, making the motor less prone to resonance. It is also important to note that this frequency depends on the load inertia, according to the formula below:

$$f = \frac{1}{2\pi}\sqrt{\frac{T_h.N}{J_R + J_L}}$$

20. **Angular Acceleration (Nominal Current).** This is mainly a figure of merit, as it is purely a theoretical calculation. This is the maximum angular acceleration in radian/second square [rad/s^2] of the rotor when the motor is energized at rated current at no-load. It can be calculated with the formula: $A_{max} = T_{holding} / J_{motor}$

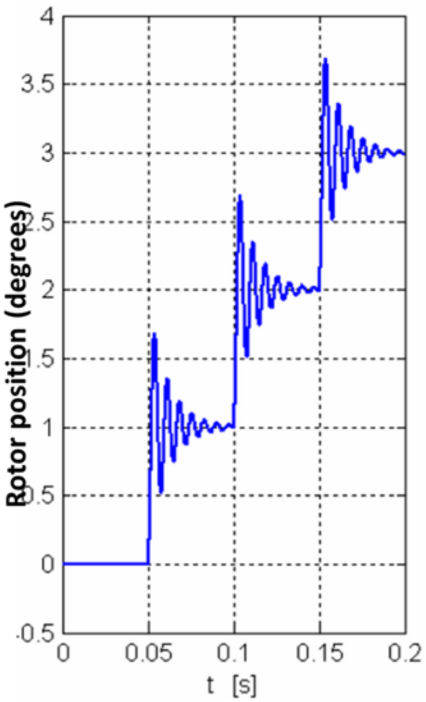


Figure 10. Oscillation of the Rotor Around the Stable Position at Each Motor Step.

Conclusion

Though stepper motors may be less intuitive than other motor technologies, they are nevertheless an excellent option for powering a wide variety of applications. We hope that the above discussion provides a greater understanding of stepper motors, especially in regard to their technology, key performance parameters, and the unique terminology that surrounds them. Portescap's motion experts have decades of experience of engineering stepper motors for applications within the medical and industrial sectors. Reach out today for assistance.

Matthieu Bouat
Application Engineer
Portescap
A REGAL REXNORD BRAND

FOR MORE INFORMATION:

110 Westtown Road
West Chester, PA 19382
T: +1 610 235 5499
F: +1 610 696 4598
sales.america@portescap.com
www.portescap.com

CONTACT AN ENGINEER:
www.portescap.com/en/contact-portescap