TECHNICAL ARTICLE

Mastering Precision: Understanding Microstepping in Motion Control

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Abstract

Stepper motors are vital in precision applications where there is a need for smooth movement and high resolution positioning. Recognizing the differences between fullstepping, halfstepping, and microstepping control is essential for meeting these requirements. This article closes the knowledge gap by summarizing the basics of microstepping.

Introduction

Stepper motors are widely used in industrial, medical, and 3-axis positioning system applications such as 3D printers and computer numerical control (CNC) machines, due to their precision and relatively simple control schemes. Although AC motors and brushless DC motors can obtain high precision, stepper motors have the additional advantage of high precision while operating with open-loop control and having high torque at low velocity. Additionally, stepper motors are often more cost-effective and less complex than servo motors. Unlike brushed DC motors, stepper motors can hold their position with high torque.

Microstepping is highly useful in stepper motor control by allowing the motor to move by smaller increments, resulting in a significant increase in the number of discrete positions per revolution and a subsequent decrease in motor noise and vibration. Analog Devices' Trinamic Motion Control has stepper motor driver ICs, board-level modules, and complete solutions that are capable of operating stepper motors with up to 256 microsteps.

Stepper Motor Basics

Motor Construction

A stepper motor, frequently referred to as a stepper, consists of a magnetic rotor and stator coils. Hybrid 2-phase steppers have a rotor with two magnetic cups, each with typically 50 teeth as shown in Figure 1. These magnets have opposite magnetic polarity and are physically offset from each other. The stator consists of two coils of wire placed in multiple positions around the central rotor. Energizing each phase in sequence causes the motor to rotate.

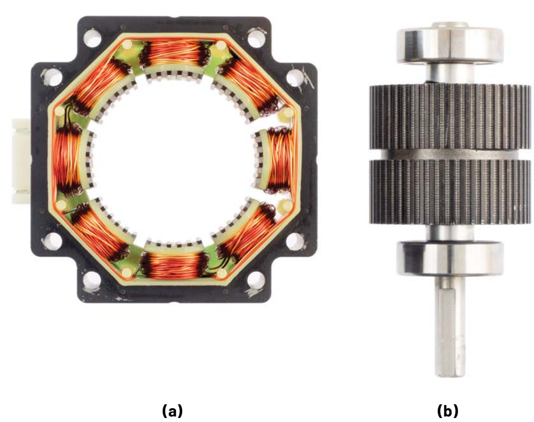

Figure 1. Hybrid stepper motor construction. (a) 8-pole stator. (b) Permanent magnet rotor.

Operation

A stepper motor moves in discrete steps by dividing a full rotation into equidistant steps. For instance, a stepper motor with 200 discrete positions per revolution of the motor will have a 1.8°

step angle. The step angle is derived from dividing the 360° of a revolution by the number of full steps.

$$Step\ Angle = \frac{360^{\circ}}{\#\ of\ Full\ Steps} \qquad (1)$$

As shown in Figure 2, when current is applied to the motor's coils, a magnetic field is produced that attracts or repels the permanent magnet rotor, and the rotor will rotate to align with this magnetic field. To keep the motor rotating, each coil must be alternately energized to keep the magnetic field ahead of the rotor.

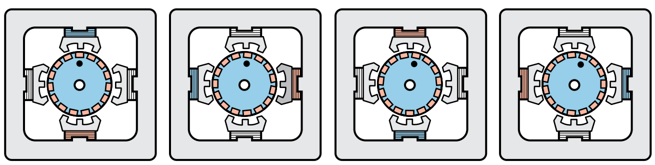

Figure 2. Hybrid stepper motor operation.

Fullstepping and Halfstepping

To better understand the stepping behavior of a stepper motor, we will evaluate a simplified 2-phase stepper motor model with one magnetic pole-pair as shown in Figure 3.

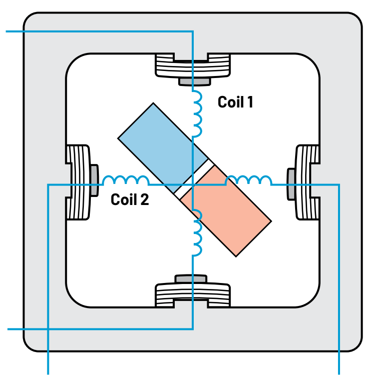

Figure 3. A simplified 2-phase stepper motor with permanent magnet rotor.

Full-Step Mode

In full-step mode, the driver energizes the two coils with either positive or negative current. Both phases are simultaneously energized, which achieves maximum torque. Switching the direction of current through the coils causes the shaft to rotate. The switching pattern, often referred to as commutation, typically adheres to the periodic sequence shown in Figure 4.

$$\begin{aligned} &Coil\ 1 = +I,\ Coil\ 2 = +I \\ &Coil\ 1 = -I,\ Coil\ 2 = +I \\ &Coil\ 1 = -I,\ Coil\ 2 = -I \\ &Coil\ 1 = +I,\ Coil\ 2 = -I \end{aligned} \qquad (2)$$

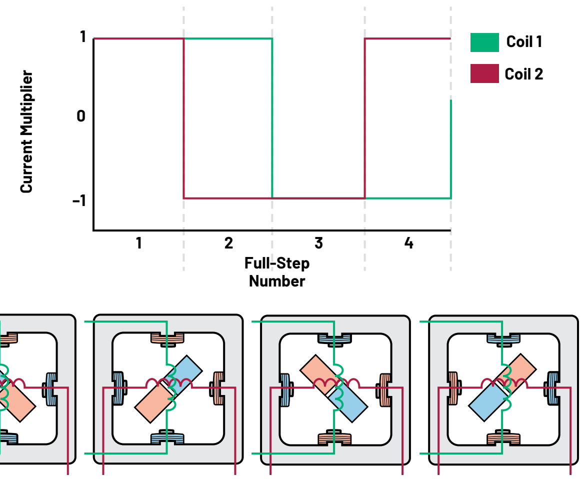

Figure 4. Full-step mode for 2-phase stepper motor.

Fullstepping allows for precise steps, speed control, and high holding torque. In addition, fullstepping can maximize a motor's torque output when operating at high speeds. However, Figure 5 illustrates how fullstepping can cause excessive vibration and noisy operation. This vibration and noise are primarily due to large position jumps that cause the motor to overshoot its target position, which results in high resonance at specific speeds and reduced applied torque.

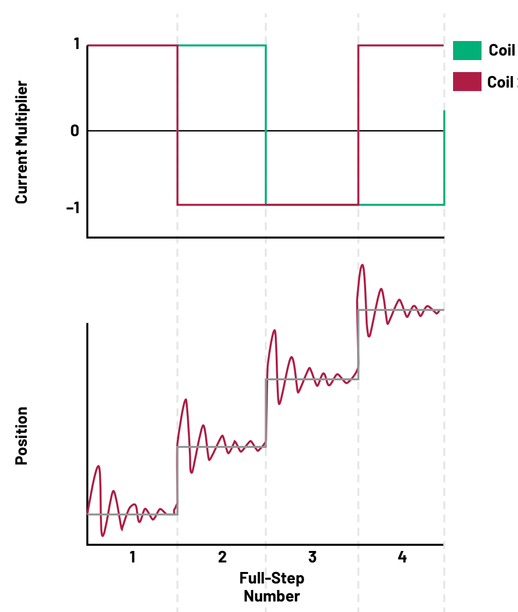

Figure 5. Fullstepping overshoot and ringing.

Since the simplified motor with a single magnetic pole-pair achieves four discrete positions per revolution using full-step commutation, expanding this concept to a motor with 50 magnetic pole-pairs translates to 200 full steps per revolution.

$$\begin{aligned} &200\ Full\ Steps\ per\ Revolution \\ &= 50\ Pole\text{-}Pairs \times 4\ Positions \end{aligned} \qquad (3)$$

The setup enables the motor to be directed to specific positions when the rotor's teeth align with the magnetic field of the coils.

Half-Step Mode

Reducing the size of the steps improves position overshoot, vibration, and noise issues. The step-size reduction can be realized by implementing an additional current state as shown in Figure 6. The half-step model increases the number of rotor positions to eight per magnetic pole-pair, which results in the doubling of position resolution. The motor driver alternates between single-phase and double-phase excitation to arrive at the half-step behavior. The half-step model allows for higher position resolution with reduced vibration. Rotational torque increases slightly at low speeds, but the motor's holding torque in the new half-step position is reduced. This is commonly referred to as incremental torque.

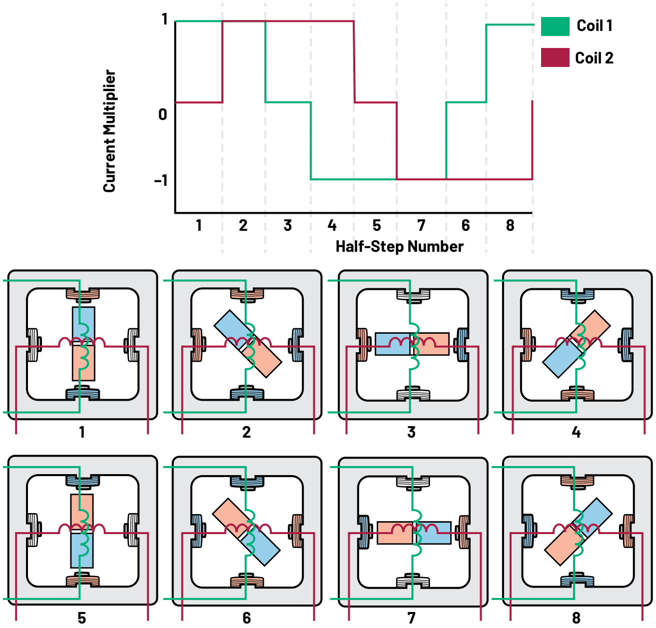

Figure 6. Half-step mode for 2-phase stepper motor.

Despite these improvements, the half-step model is not without issues. The motor still makes relatively large position jumps, meaning the motor's rotation is not perfectly smooth. The problem is especially apparent at low speeds and is the driving force behind the need for microstepping.

Microstepping

What Is Microstepping?

Microstepping is a method of controlling stepper motors such that the motor can rotate to multiple intermediate positions between full steps. It is typically used to achieve higher position resolution and smoother rotation at low speeds. This is accomplished by dividing each full step into equidistant microsteps as shown in Figure 7. Increasing the microstep resolution results in a smaller travel distance that reduces position overshoot and ringing, thus improving vibration and noise.

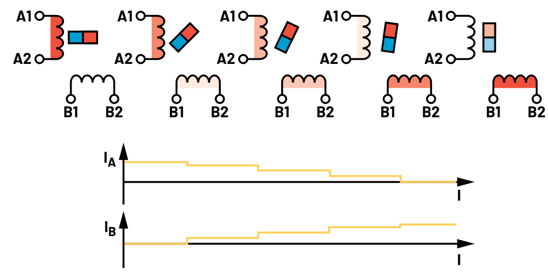

Figure 7. Current through each coil while microstepping.

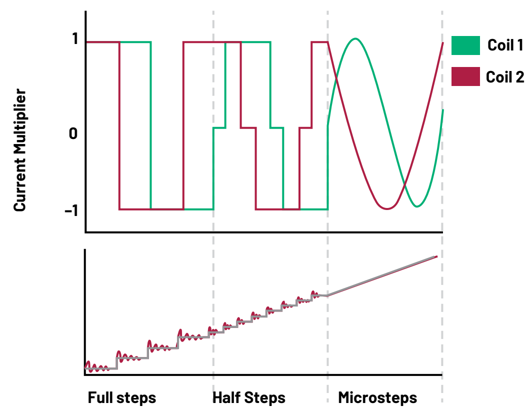

Figure 8. Comparison of current waveforms and position overshoot/ringing in different step modes.

How Does Microstepping Work?

Microstepping is implemented by providing sinusoidal waveforms to the motor as shown in Figure 8. The motor driver utilizes current regulation to precisely deliver these sinusoids to each motor coil. However, it is impossible to generate perfect sinusoids. The sinusoidal wave quality, and therefore the quality of microstepping, is limited by the resolution of the stepper driver's analog-to-digital converters (ADCs) and digital-to-analog (DACs) converters. Each of ADI Trinamic's stepper motor drivers has at least 8-bit ADCs and DACs, which enables up to 256 microsteps per full step. Since a hybrid stepper motor typically has 200 full steps per rotation, the use of 256 microsteps allows for up to 51,200 discrete positions per revolution. This results in an impressive step resolution of 0.00703125°.

Key Considerations: Positional Accuracy and Incremental Torque

Microstepping has many benefits, but it comes with two key challenges: positional accuracy and incremental torque.

Position accuracy refers to the error between the motor's actual position and its commanded position. Although microstepping increases position resolution with more discrete positions, it does not improve position accuracy. Accuracy of the motor is still a function of construction tolerance, the load on the motor, and the driver's ability to accurately provide the desired current levels to the motor coils. These limiting factors affect the motor's accuracy regardless of fullstepping or microstepping.

Incremental torque is defined as the amount of torque required to pull the motor out of position when the motor is at standstill. When using fullstepping, the magnetic rotor is perfectly aligned with the motor coils, creating maximum holding torque equal to the motor's specified holding torque. However, when microstepping is used, the incremental torque decreases based on the microstep position at which the motor is being held.

Incremental torque can be approximated using Equation 4:

$$T_{INC} = T_{HOLD} \times sin\left(\frac{90^{o}}{SDR}\right) \quad (4)$$

Where:

- T_{INC}: incremental torque in units of Newton-meters (N·m)
- T_{HOLD}: full-step holding torque in units of Newton-meters (N·m)
- SDR: step-division ratio or the denominator of simplified fraction:

$$\frac{Step\ Position}{Step\ Resolution} \quad (5)$$

The phenomena is best illustrated with a few examples. Consider a motor using 256 microsteps, stopped at a half-step position.

$$\frac{Step\ Position}{Step\ Resolution} = \frac{128}{256} = \frac{1}{2} \quad (6)$$

The SDR is simply the denominator of the simplified fraction; therefore, the SDR is 2. The incremental torque decreases to 70.709% of the motor's holding torque.

$$T_{INC} = T_{HOLD} \times sin\left(\frac{90^{\circ}}{2}\right) = T_{HOLD} \times 0.70709 \quad (7)$$

As another example, when the motor is stopped at a 7/256 microstep position:

$$\frac{Step\ Position}{Step\ Resolution} = \frac{7}{256} \quad (8)$$

Therefore, the SDR is 256 and the incremental torque drops to 0.61% of the motor's holding torque.

$$T_{INC} = T_{HOLD} \times sin\left(\frac{90^{\circ}}{256}\right) = T_{HOLD} \times 0.00614 \quad (9)$$

The relationship between SDR and incremental torque is summarized in Table 1.

Table 1. Incremental Torque

SDR	T_{INC} / T_{HOLD}
1	100.00%
2	70.709%
4	38.267%
8	17.508%
16	9.801%
32	4.907%
64	2.454%
128	1.227%
256	0.614%

Importantly, while incremental torque reduces the torque available to hold the motor in these microstep positions, rotational torque is largely unaffected. When the motor is rotating, the effects of reduced incremental torque will not be seen. From a practical standpoint, if high holding torque is needed, the user should try to stop the motor on full-step or half-step positions.

Common Microstepping Applications

Many applications using stepper motors stand to benefit from microstepping. As an example, 3D printing requires high position resolution and minimum vibration in order to produce high quality prints. Medical imaging and surgical robotics need quiet operation and precise positioning to ensure patient comfort and safety. Microstepping fulfills these requirements.

In addition, due to the smaller step size, position overshoot is significantly reduced. This brings a number of advantages: decreased vibration, increased efficiency, and smoother motion. Mechanical vibration consumes energy and, in some applications such as CNC milling machines, introduces extra wear and compromises reliability. By reducing mechanical vibration and noise, microstepping also reduces waste in the cost and energy associated with operating a motor control system.

Other applications that use microstepping include medical research equipment, valve control, air pumps, CCTV, robotics, and factory automation.

ADI Trinamic Solutions

ADI Trinamic's stepper motor products offer various features that can assist with incorporating microstepping. Microstepping, up to 256 microsteps, is standard for all of ADI Trinamic's stepper motor products.

In addition, some ADI Trinamic parts offer MicroPlyer™ technology, a microstep interpolation technique meant to enable older applications to easily utilize high microstep resolution.

The ADI Trinamic product portfolio includes complete, efficient, and small footprint solutions to support any space and performance requirements. These parts can help reduce complexity and time to market in stepper motor applications.

MicroPlyer Microstep Interpolator

A resolution of 256 microsteps might be beyond the capability for stepper drivers from some manufacturers. Fortunately, ADI Trinamic's MicroPlyer technology allows lower step resolution systems to upgrade to 256 microsteps without needing to modify the motion control logic.

MicroPlyer works by incorporating additional current steps between step pulses while preserving position and velocity. The unit interpolates the time in between step pulses by measuring the time interval of the previous step period and dividing it into equal parts. This creates an internal 256-microstep STEP signal that is used to drive the motor. The result is smooth, 256-microstep output, despite being provided a low resolution step-signal input. As such, ADI Trinamic stepper motor drivers are ideal for drop-in replacements to existing applications.

As an example, a designer may want to upgrade a 16-microstep driver and system to achieve smoother motion with 256 microsteps. If the desired speed is 10 revolutions per second (RPS) with a 1.8° step angle motor, the input STEP signal would need to be 32 kHz when using 16 microsteps. Typically, a 200 full-step motor with 256 microsteps would need a 512 kHz signal frequency for a rotation of 10 RPS. This might be too high of a frequency for some host controllers or MCUs. Alternatively, the designer can drop in an ADI Trinamic driver that supports MicroPlyer and keep the 32 kHz STEP signal. The ADI Trinamic driver will handle the interpolation of the STEP signal to create motion using 256 microsteps as shown in Figure 9.

TMC2240 36 V, 2 A rms + Smart Integrated Stepper Driver with S/D and SPI and TMC5240 36 V, 2 A rms + Smart Integrated Stepper Driver and Controller

ADI's TMC2240 and TMC5240 are smart, high performance, 2-phase stepper motor driver ICs with serial communication interfaces (SPI, UART), extensive diagnostic capabilities, and microstep interpolation with MicroPlyer technology. These driver ICs combine an advanced stepper motor driver based on 256 microsteps, a built-in indexer, and two fully integrated 36 V, 3.0 AMAX H-bridges plus nondissipative integrated current sensing (ICS). With best-in-class motion and current control, the TMC2240 and TMC5240 feature smooth and silent stepper motor motion with the complete set of ADI Trinamic features for increased power efficiency CoolStep™, sensorless load and stall detection (StallGuard2™/StallGuard4™), silent operation (StealthChop2), and ripple-reducing current control (SpreadCycle™). The SpreadCycle and StealthChop2 chopper modes allow for minimum noise operation at a wide range of speeds with automatic switching between SpreadCycle and StealthChop2. ADI Trinamic's sophisticated StealthChop2 chopper ensures noiseless operation combined with maximum efficiency and best motor torque. The TMC5240 is a cDriver™ IC that goes beyond typical motor drivers by integrating a motion controller, allowing for a simplified system architecture. The integrated 8-point motion ramp allows the user to program a desired position and motion profile, minimizing jerk and offloading the necessary calculations from the host controller.

These products feature diagnostics and protections such as short or overcurrent protection, thermal shutdown, and undervoltage lockout (UVLO). During thermal shutdown and UVLO events, the driver is disabled to prevent damage from occurring. Furthermore, these devices provide functions to measure one external analog input, assess the driver temperature, and estimate the motor temperature.

High integration, high energy efficiency, and a small form factor enable miniaturized and scalable systems for cost-effective solutions. Internal current sensing eliminates the need for bulky external current-sense resistors. The complete solution gives the best-in-class performance and reduces the learning curve to a minimum.

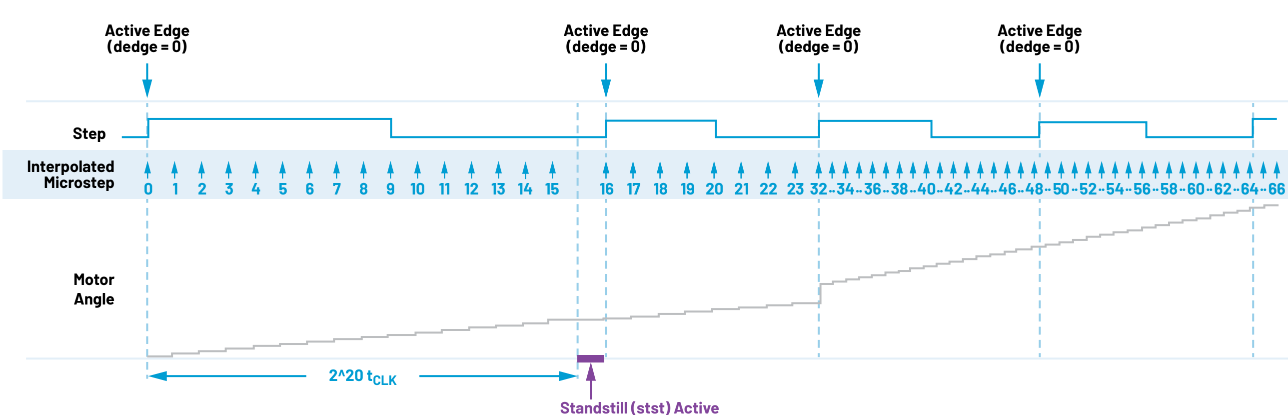

Figure 9. Simplified example of MicroPlyer Microstep Interpolator, interpolating from fullstepping to 16 microsteps.

Both of these products can be used in applications such as medical instrumentation, lab and factory automation, CCTV, security, and 3D printers.

TMC2160 High Voltage Driver for Bipolar Stepper Motor and TMC5160 High Voltage Driver and Motion Controller for Bipolar Stepper Motor

The TMC2160 and TMC5160 are high power, 2-phase stepper motor driver ICs with serial communication interfaces (STEP/DIR, SPI, UART), 256-microstep resolution, and microstep interpolation with MicroPlyer. These ICs utilize a variety of ADI Trinamic features including CoolStep, StealthChop2, StallGuard2, and SpreadCycle to optimize driver performance. The TMC5160 is a cDriver IC with an integrated motion controller featuring SixPoint™ ramping for faster positioning and mitigated resonance caused by trapezoidal ramping.

These ICs do not have integrated FETs, allowing for flexibility with FET selection to accommodate high currents and/or high voltages. This versatility allows for a wide spectrum of applications from battery-powered systems to high voltage industrial applications.

Both of these products can be used in applications for medical, textile, robotics, and industrial drives as well as CCTV, security, and factory automation.

TMC2300 Low Voltage Driver for 2-Phase Stepper Motors

The TMC2300 is a low voltage stepper motor driver for 2-phase, battery-powered stepper motors. This driver includes a 256-microstep resolution in addition to CoolStep, StealthChop2, StallGuard4, and SpreadCycle features. StealthChop2 enables silent motion control for portable, home, and office applications. The TMC2300 utilizes STEP/DIR interface for up to 256 microsteps with an optional UART interface for advanced configuration. A highly efficient power stage and a tiny standby current of 0.03 μA help to guarantee a long battery life. Dual AA or single Li-Ion batteries used with this driver can be drained down to typically 2.0 V.

The TMC2300 driver provides high motor current from a tiny 3 mm × 3 mm package and is suitable for IoT, handheld devices, battery-operated equipment, and mobile medical devices.

Conclusion

Microstepping offers numerous benefits across diverse stepper motor applications. When high efficiency, precise positioning, and minimal noise are crucial factors, incorporating microstepping with ADI Trinamic solutions becomes highly advantageous. All of ADI Trinamic's stepper motor products have a 256-microstepping capability and makes upgrading existing systems with microstepping a simple task.

Reference

[1]George Beauchemin. "Microstepping Myths." Machine Design 75, No. 19, October 2003.

About the Authors

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