Application Report

How to Improve Motion Smoothness and Accuracy of Stepper Motors

ABSTRACT

It is common for most stepper motor systems to operate with an open loop control scheme. Since there is no position or velocity feedback coming back to the stepper motor driver which is controlling the position of the motor, the stepper motor driver is essentially running blind. Traditional stepper motor drivers with poor channel-to-channel current matching, low current sense accuracy and low levels of microstepping result in choppy and inaccurate motion, but state of the art drivers with better current matching and high levels of microstepping can help improve the accuracy significantly. This application report explains how specific motor driver features can improve the quality of motion for a wide variety of stepper motor systems and applications.

Table of Contents

List of Figures

List of Tables

Trademarks

All other trademarks are the property of their respective owners.

1 Introduction

The majority of stepper motor systems do not include an encoder to sense the position and provide feedback to the MCU. With traditional stepper drivers, stepper motors can oscillate around their destination, or have a different angular position increment after each microstep, resulting in poor positional accuracy. *Stopping accuracy* of a stepper motor is the difference between the actual stop position and theoretical stop position. The higher the stopping accuracy, the better the quality of the end product, such as clearer and more crisp printing.

- In a 3D printer, the quality of printing depends on the position accuracy of the stepper motors controlling movement of the extruder and of the printer bed in the X-Y-Z directions.
- For a stage lighting module, precise positioning of the light beam is critical; any vibration or speed fluctuations of the stepper motor will make the light unstable.
- For a security camera, features such as video facial recognition requires the stepper motors to have very accurate positioning and smooth operation over a wide range of speed to prevent image distortion.

The following sections discuss the various factors that affect the accuracy of stepper motors as well as how stepper motor drivers can help improve the accuracy.

2 Various Factors Affecting Stepper Accuracy

There are various mechanical and electrical factors that come into play which affect the positional accuracy of a stepper motor.

2.1 Mechanical Factors

These are related to the construction of the stepper motor arising from imperfections in the magnetic and mechanical construction of the motor, and are not under control of the stepper motor driver.

- The precision to which the stator and rotor are punched and assembled.
- The concentricity of the air gap between the rotor and the stator. If the variation in the airgap increases, step error also increases proportionally.
- Higher torque stiffness of the rotor causes oscillations back and forth between steps.
- Motor linearity refers to how the motor moves between its intended locations. In practice, all stepper motors exhibit some non-linearity, meaning the microsteps bunch together rather than being spread evenly over the span of a full step. This leads to poor stopping accuracy.

2.2 Electrical Factors

Unlike the mechanical factors, the electrical factors can be greatly improved by selecting the right stepper motor driver.

2.2.1 Stepper Driver Channel-to-Channel Current Matching

A stepper motor driver has two electrical current windings and each winding is typically controlled with an H-Bridge. As Figure 2-1 shows, the stepper motor driver applies current waveforms approximating a sine wave into one coil (I_A = coil A current) and a cosine wave into the other coil (I_B = coil B current).

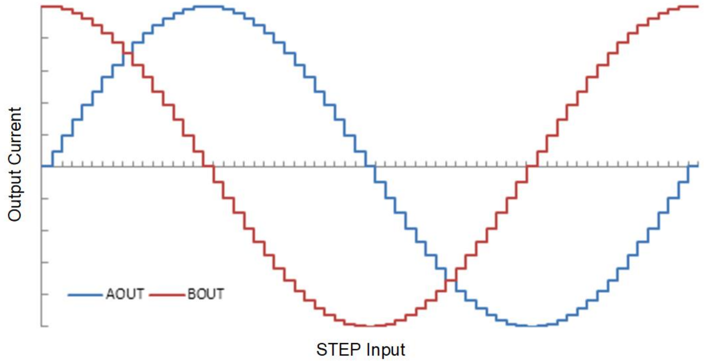

Figure 2-1. Stepper Motor Coil Current Waveform

The output torque and angular position of a stepper motor are controlled by the magnitude of the currents flowing thorough the two windings. The output current of a stepper motor driver can be expressed as:

$$IOUT = \sqrt{I_A^{\,2} + I_B^{\,2}}$$

The angular position can be expressed as:

$$\theta = \tan^{-1}\frac{I_B}{I_A}$$

To ensure that the output current is constant and the incremental angle is the same in each microstep, ideally one coil current should be a pure sine wave, and the other coil current should be a pure cosine wave, phase-shifted by 90° from the other. The two coil currents must maintain this relation as much as possible, and any mismatch from ideal values will cause non-uniformity in the angular position increments and will lead to uneven output torque. The motor will step by a different amount of angle at each microstep, leading to position inaccuracies. Also, at higher speeds, the inaccuracies can cause short-term speed variations within a single rotation of the motor, which can lead to an increase in motor vibration.

As an example, assume a situation where I_A and I_B are both 1 A, such that the expected electrical angle of the stepper motor is 45° and the expected output current is 1.414 A. If the coil B current deviates by +5% from the expected value, the angle becomes 46.4° instead, which is 3% higher than the expected value and might be enough to distort the quality of image in a security camera application or make text unreadable. The output current also increases by 2.5% from the target value, decreasing the efficiency of the system.

Most legacy stepper drivers have a channel-to-channel current accuracy of ±5% or worse. However, the DRV84xx family of stepper drivers from Texas Instruments (such as the DRV8428, DRV8426, DRV8424, DRV8889-Q1, DRV8899-Q1, and DRV8436, and so forth) have an improved channel-to-channel current accuracy of only ±2.5% in worst case, which results in excellent stopping accuracy of the stepper motor.

Figure 2-2 shows the stopping accuracy of DRV8424 running at 1000 pps speed with 1/8 microstepping, 2-A full-scale current setting and smart tune ripple control decay mode. The plot shows ±0.03° maximum angular error while driving an unloaded stepper motor with 1.8° step angle. For a motor with 1.8° step angle, ±0.05° or less stopping accuracy is considered excellent.

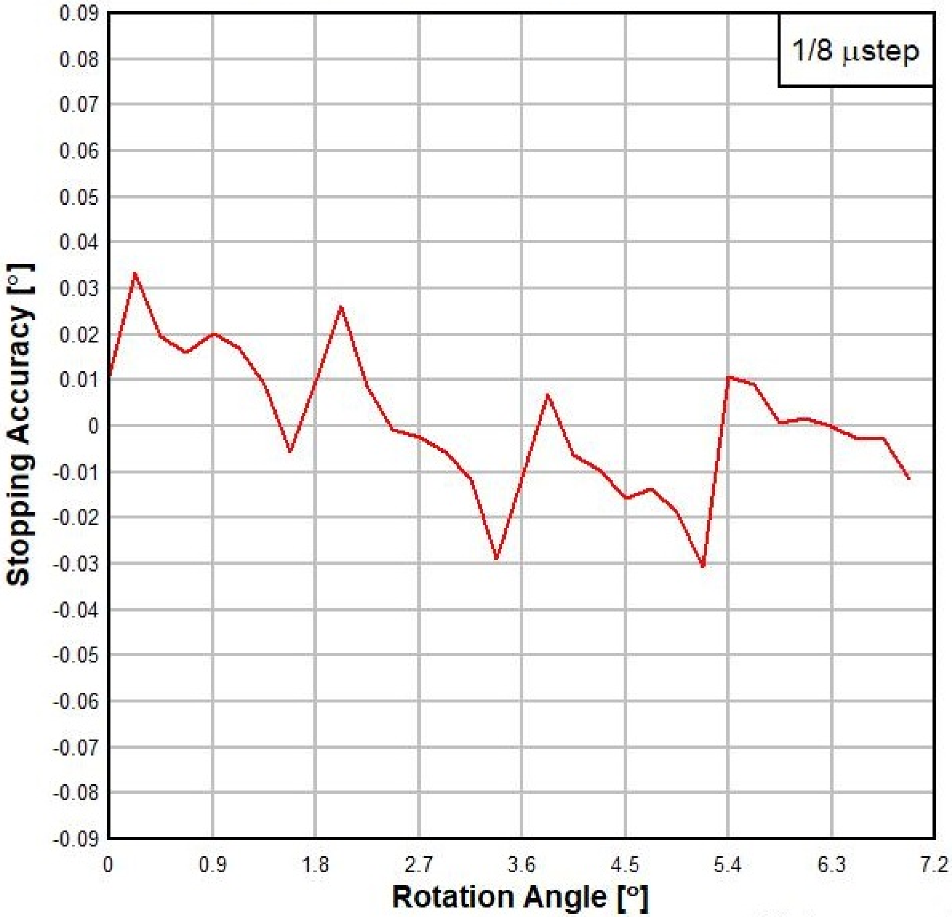

Figure 2-2. Stopping Accuracy of DRV8424

2.2.2 Stepper Driver Decay Mode

The smoothest operation of a stepper motor happens when perfect sinusoidal current waveforms are applied to the windings. Any ripple in the current waveform is a deviation from the desired shape and causes an uneven torque and incremental angle of the motor, which manifests as vibration and poor accuracy.

To reduce the ripple, it is recommended to operate a stepper motor on slow decay mode whenever possible, instead of fast or mixed decay. However, due to back-emf, mixed decay modes are better at following the ideal sinusoidal current waveform, especially at high speeds and on decreasing steps, compared to slow decay. Therefore, a slow decay mode which can follow the ideal waveform at all conditions is the ideal candidate for improving accuracy.

Smart tune ripple control, available in the DRV84xx and DRV88x9-Q1 family of drivers and few other stepper drivers from Texas Instruments is a special slow decay scheme that circumvents this problem by automatically switching to fast decay to reach the next decreasing step quickly - which enables it to follow the ideal sinusoidal current waveform at all speeds.

Figure 2-3 shows the stopping accuracy of DRV8424 running at 500 pps speed with 1/4 microstepping, 2-A full-scale current setting and with smart tune ripple control and mixed 30% decay modes. Clearly smart tune results in better accuracy.

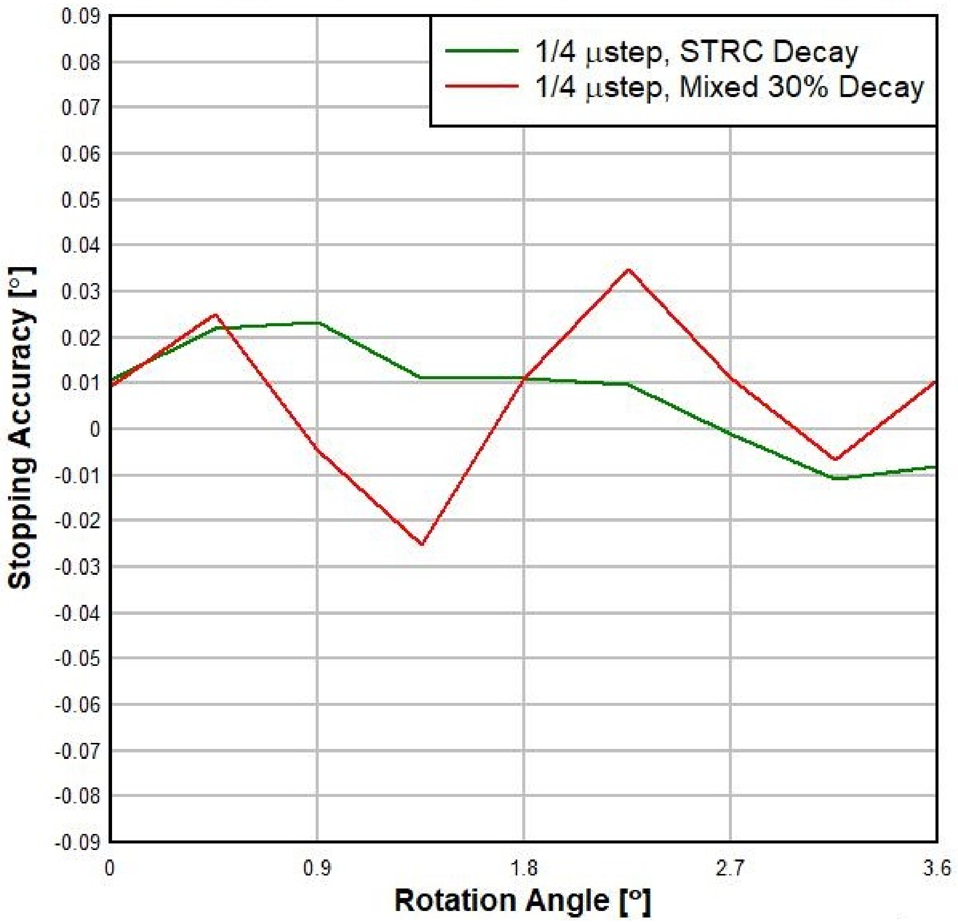

Figure 2-3. Stopping Accuracy at Different Decay Modes

2.2.3 Microstepping Levels

Operating a stepper motor in full-step mode causes the motor to jump by one step angle (1.8° mechanical rotation in most cases), resulting in overshoot, torque ripple, and vibrations. As a result, most stepper drivers today incorporate microstepping, which splits the full-step into smaller equal segments, and therefore provides capability of smooth stepping and accurate positioning.

One effect of microstepping is to reduce the vibration of the stepper motor, by smoothening the motion of the motor to its intended location. For example, in a printer, any vibration will result in poor printing quality. By using microstepping, vibration can be significantly reduced and consequently, printing quality can be improved.

The DRV84xx and DRV88x9-Q1 family of stepper drivers feature microstepping up to 1/256 levels, leading to easy adaptability to any application that requires high accuracy and smooth stepper movement. The following plot shows similar accuracy with 1/4, 1/8 and 1/16 microstepping for the DRV8424.

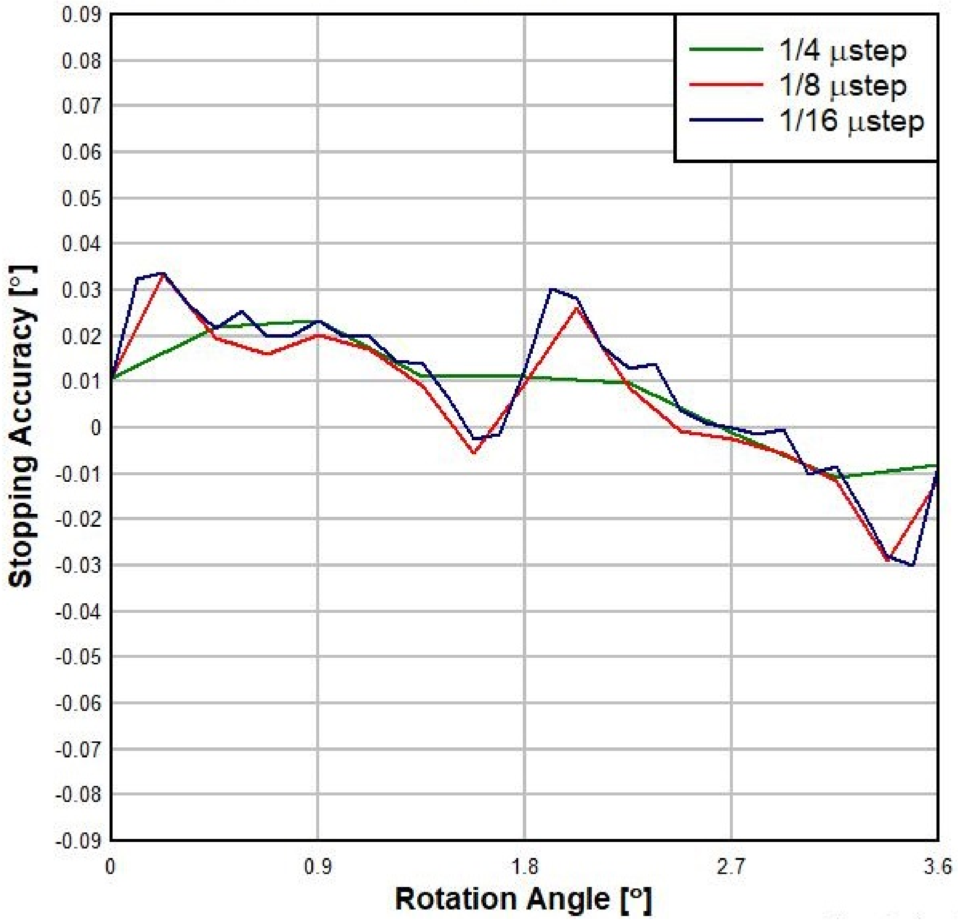

Figure 2-4. Stopping Accuracy at Different Microstepping

However, as the number of microsteps per full step is increased, the incremental torque per microstep reduces significantly. The expression for incremental torque for a single microstep is:

$$T_{INC} = T_{HFS} \times \sin(\frac{90^\circ}{N})$$

Where T_{INC} is the incremental torque per microstep, T_{HFS} is the holding torque in full step and N is the number of microsteps per full step. Table 2-1 shows the variation of incremental torque:

Table 2-1. Incremental Torque Variation with Number of Microsteps

Microsteps per Full Step	% Holding Torque per Microstep
1	100%
2	70.7%
4	38.3%
8	19.5%
16	9.8%
32	4.9%
64	2.5%
128	1.2%
256	0.6%

Therefore, a motor running in full steps will have 100% of its rated holding torque. Moving to 16 microsteps/full steps drops this to approximately 10%, and 1/128 microstepping drops incremental torque to approximately 1% of holding torque. If the incremental torque is less than the sum of the load torque, the friction torque (due to bearings) of the motor, and detent torque, multiple microsteps will have to be realized until the motor shaft can actually turn. If reversing direction is desired, a significant number of microsteps may be needed before movement occurs.

Therefore, higher microstepping will result in better positional accuracy only if the incremental torque is more than the torque needed to move the load. Many motor manufacturers have recommendations on the highest level of microstepping that can be used for that motor.

2.2.4 Stepper Driver Current Sense Accuracy

Open-loop stepper motors are prone to step loss, for example, when the load torque is more than the torque produced by the stepper motor. Stepper motors lose synchronization and positional accuracy as a result of step loss. In most applications the full-scale current is selected in such a way that step loss does not happen due to unexpected load peaks. Therefore, the torque output of the stepper motor is often 40–50% higher than the maximum load torque expected in the application.

The margin between the full-scale current and load has to be calculated by taking into account the worst case current sense accuracy. When the current sense accuracy is poor, the full-scale current setting has to be parked higher to prevent step loss and loss of accuracy. Therefore, better current sense accuracy allows the selection of a lower value of full-scale current rating of the stepper driver, which indirectly leads to better positional accuracy of the system by preventing step loss, while minimizing power loss. The DRV84xx family of stepper drivers feature ±5% maximum current-sense accuracy over operating voltage range, process and temperature.

3 Conclusion

Positional accuracy of stepper motors can be a critical challenge for designers to overcome. But with the right motor driver, accuracy can be significantly improved by utilizing a number of different features. In addition to featuring best-in-class channel-to-channel current accuracy, motor drivers from Texas Instruments provide automatic decay mode control with smart tune technology, up to 1/256 microstepping, and high current sense accuracy to ensure smooth motion and highly accurate stepping. For more information on TI’s stepper motor products, see TI.com.

4 References

- *Stepper Motor Technical Note: Microstepping Myths and Realities*
- *Inkjet Printer Print Quality Enhancement Techniques*
- Texas Instruments, *DRV8889-Q1, DRV8889A-Q1 Automotive Stepper Driver with Integrated Current Sense, 1/256 Micro-Stepping, and Stall Detection Data Sheet*

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale (www.ti.com/legal/termsofsale.html) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2020, Texas Instruments Incorporated