Application Note #5452

Microstepping Performance: Resolution, Accuracy & Repeatability

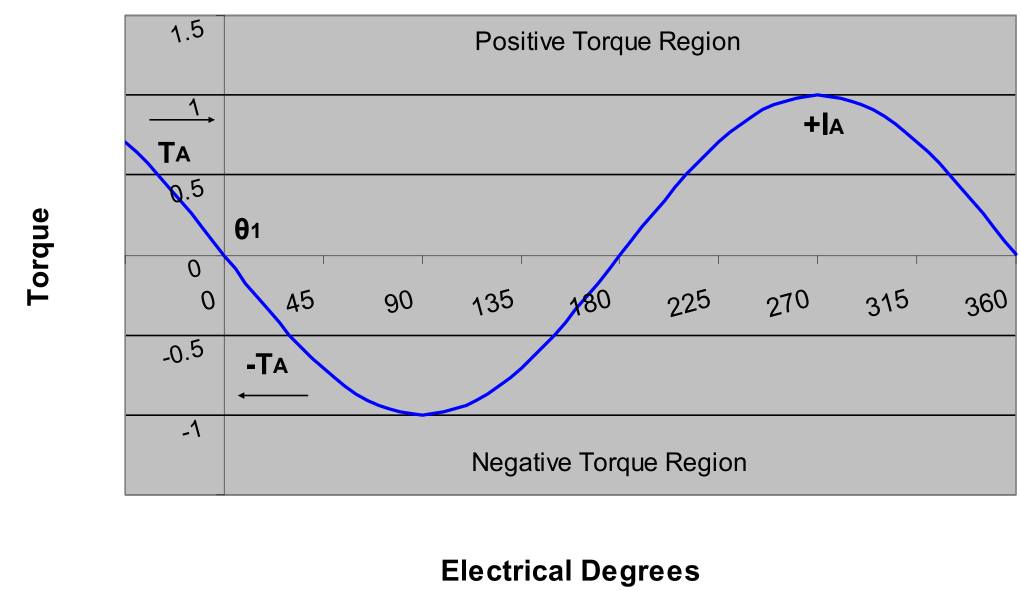
Introduction

Microstepping is a method for controlling stepper motors. It offers improved performance by providing finer position steps, reduced vibration, and smoother motion. However, microstepping has limitations on performance. We will discuss these limitations, and how to analyze them to predict realistic microstepping performance. Let us first start with the control modes of stepper motors.

Full Step Mode

When we apply a positive current through Phase A, it produces a torque. Fig.1 shows the torque vs. position in electrical degrees.

Fig. 1: Phase A Positive Current Torque Curve



If the motor is positioned less than position θ_1 it sees a positive torque and moves forward. If the motor begins at a position greater than θ_1 it sees a negative torque and moves back. In either case the motor moves to θ_1, the stable equilibrium point of phase A with positive current flow. To move the motor

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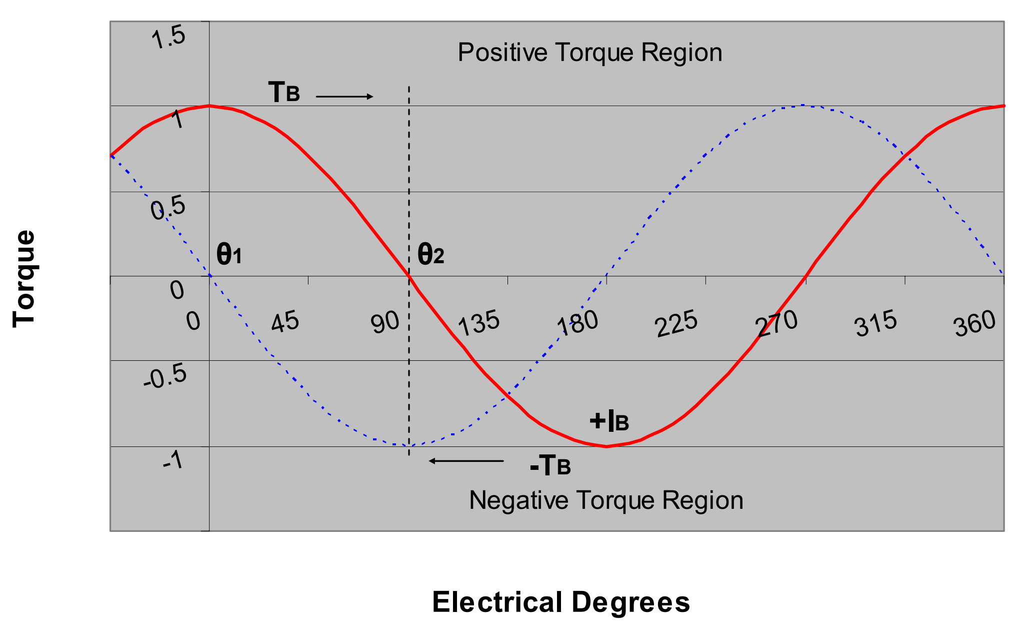
forward we switch off Phase A and activate Phase B with a positive current. The resulting move from θ_1 shown in Fig.2, is the equilibrium point of Phase B, θ_2.

Fig. 2: Phase B Positive Current Torque Curve



To move the motor continuously, we then switch current off Phase B and back onto Phase A with a negative current. This inverts the torque curve profile of Phase A from Fig. 1, creating forward torque at the previous equilibrium position, θ_2. This effect keeps the motor moving to the next equilibrium position, θ_3.

Fig. 3: Phase A Negative Current Torque Curve

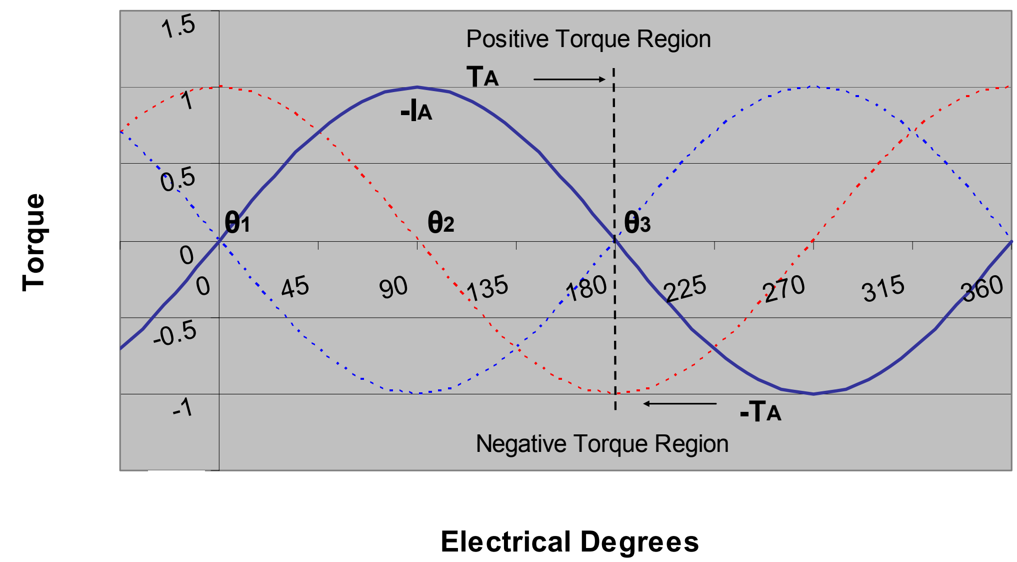


Fig. 3 superimposes the negative current flow for Phases A along with the previous positive current flows and the associated forward motion equilibrium positions θ_1, θ_2, θ_3. The reverse direction for the motor is executed in the same manner, by simply following Fig. 3 from right left to switch the current on for reverse torque at each equilibrium position. This current switching control mode is known as the Full Step mode.

Full Step Current Conditions:

$$I_A = \pm 1 \ \&\ I_B = 0$$

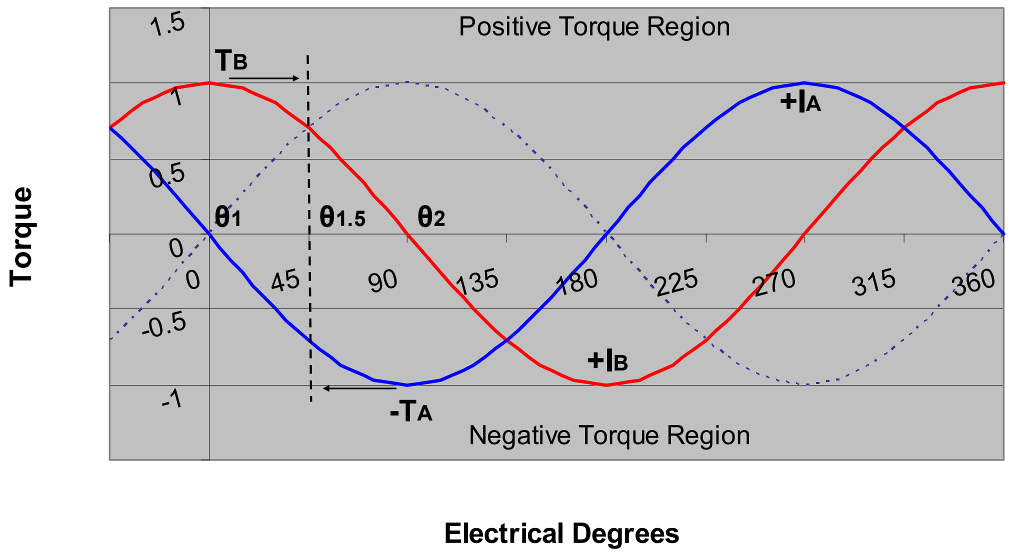
$$I_A = 0 \ \&\ I_B = \pm 1$$

But what about the intermittent positions between these equilibrium positions. Can we go there as well? This is where the Half Stepping control mode comes in.

Half Step Mode

Half stepping requires switching current on to both phases at the same time, effectively halving the step angle.

Fig. 4: Phase A & B Positive Current Torque Curves



In Fig. 4 we see that Phase A positive current and of Phase B positive current cause the motor to stop in-between θ_1 & θ_2. This half step position $\theta_{1.5}$ results from the sum of the opposing torques.

$$-T_A + T_B = 0$$

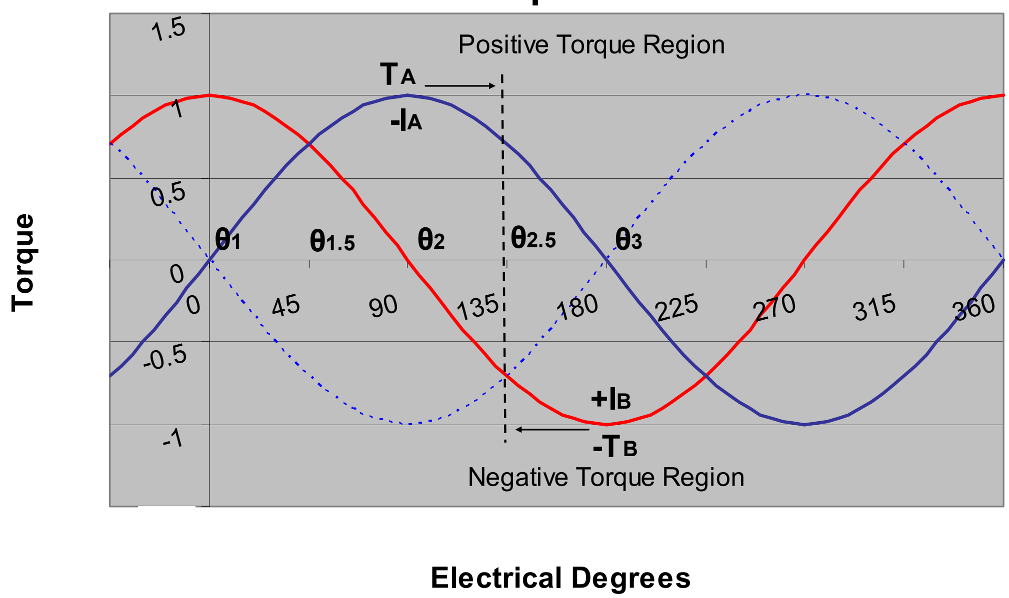
Halfstep Postion: $\theta_{1.5}$

To continue halfstepping forward we turn off Phase A to allow θ_2 position(as previously defined in Fig. 2), and then switch on negative current to Phase A. In Fig. 5, Phase B positive current is causing backward torque toward full-step equilibrium θ_2, yet Phase A negative current is causing forward torque to the next full step equilibrium θ_3. The next halfstep position $\theta_{2.5}$ results from the sum of the opposing torques.

$$T_A + -T_B = 0$$

Halfstep Postion: $\theta_{2.5}$.

Fig. 5: Phase A Negative, Phase B Positive Current Torque Curves



Halfstep Current Conditions:
$I_A = 1$ & $I_B = 1$
$I_A = -1$ & $I_B = 1$
$I_A = -1$ & $I_B = -1$
$I_A = 1$ & $I_B = -1$

What is Microstepping?

So what about further step angle resolution? If the current is continuously controlled, then positions in-between half-step positions are possible. This is the essence of the microstepping control mode. It allows smaller step angles and also results in smoother motion at lower speeds, reduced torque ripple and less vibration. To find out the motor position in microstepping mode, we need to run the following analysis.

First note that the torque curves of Fig. 1 and Fig. 2 can be expressed as

$$T_A = -KI_A\mathrm{Sin}(\theta) \qquad \text{(Eq.1a)}$$

and

$$T_B = KI_B\mathrm{Cos}(\theta) \qquad \text{(Eq.1b)}$$

where K is a torque constant associated with the specific motor.
The motor will move to the point where the net torque is zero, or, where

$$T_A + T_B = T_g = 0 \qquad \text{(Eq.2)}$$

Thus,

$$-KI_A Sin(\theta) + KI_B Cos(\theta) = 0$$

Dividing by K leads to

$$-I_A Sin(\theta) + I_B Cos(\theta) = 0$$

Which can be written as

$$Tan(\theta) = I_B/I_A$$

Leading to the position

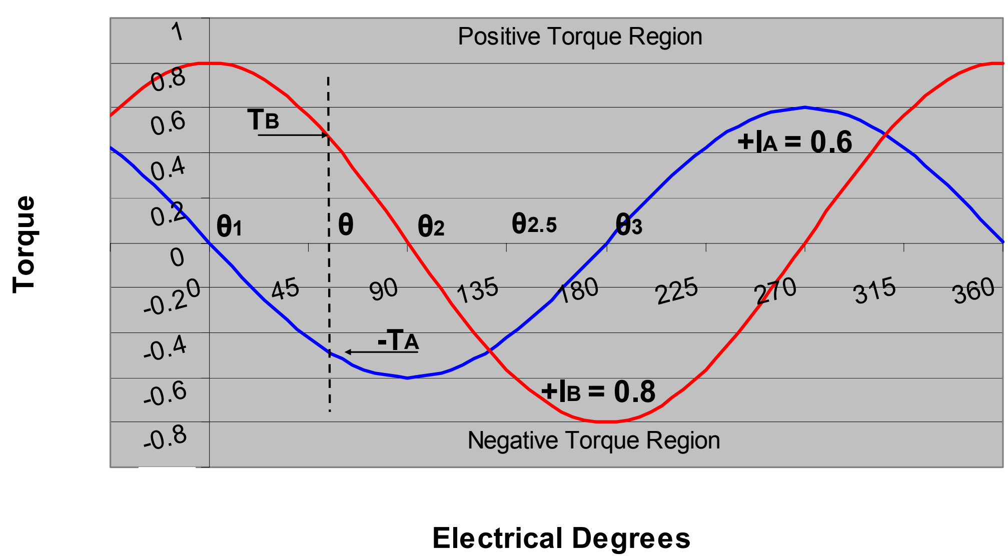
$$\theta = Tan^{-1}(I_B/I_A) \qquad \text{(Eq. 3)}$$

To illustrate the analysis, consider the case where the motor currents are

$I_A = 0.6$ A
$I_B = 0.8$ A

According to Eq. 3, the resulting position is 53.16°.

Fig. 6: Phase A & B MicroStep Torque Curves



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At this position, the torque generated by Phase A is opposed by the torque of Phase B, with a net torque of zero. By changing I_A and I_B we can reach intermediate positions of a very fine resolution.

Now that we have a refreshed our background of the control modes of stepper motors, let's turn our attention to the main topic of the discussion, the realistic performance of the microstepping.

Performance

Resolution, Accuracy, and Repeatability describe microstepping performance.

> **Resolution** is the commanded position increment.
> **Accuracy** is the absolute position error relative to commanded position.
> **Repeatability** is the relative position error over many commanded positions.

To clarify the terms, let's consider a sample system of a drive and motor with a resolution of 12,800 microsteps/revolution, or 35.6 counts per degree. From here on, counts will be synonymous with microsteps.

> Commanded move from 0 is 1000 counts: $\theta_o = 1000$
> Actual motor position ends up at 950 counts: $\theta_A = 950$
> After repetition of the two moves, the position is observed to fluxuate 5 counts on either side of the actual positions: $\theta_{AR} = 945 - 955$

Therefore,

> Resolution = 35.6 counts/degree
> Accuracy = +/- 50 counts
> Repeatability = +/- 5 counts

In this system, which is true for all systems, resolution does not guarantee actual position accuracy. The true performance of a step motor and drive is reduced by many sources of error. The following table consolidates the performance errors into general sources.

Sources of Error Affecting Performance

Source	Affects Accuracy	Error is Repeatable
Total Static Friction	Yes	No
Motor Torque Harmonics	Yes	Yes
Drive Bias	Yes	Yes
Quantization Effects	Yes	Yes

Table 1. Sources of Position Error

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Two Types of Error: Non-Repeatable & Repeatable

There are two types of errors, those that are non-repeatable and those that are repeatable. Non-repeatable errors are unpredictable, within a range, and have the greatest affect on accuracy. Repeatable errors produce predictable, repeatable effects upon accuracy.

Non-Repeatable

Non-repeatable position error is known as Absolute Position Error. Looking to Table 1, the total static friction of the motor and load affects accuracy, and the position error is not repeatable. This is due to the inherent variability of the torque induced by friction. It is important to understand that this error cannot be improved upon by motor or drive resolutions that are better than the magnitude of the error. The following is a brief derivation of the equation used to calculate this error.

Current is controlled to the phases by the following equations

$$I_A = I_o \, Cos(\theta_C) \qquad \text{(Eq. 4a)}$$
$$I_B = I_o \, Sin(\theta_C) \qquad \text{(Eq. 4b)}$$

where θ_C is the commanded position in electrical degrees and I_o is the nominal current. By substituting Eq. 4a & 4b into Eq. 1a & 1b and then the into Eq. 2

$$T_g = KI_o[-Cos(\theta_C)\, Sin(\theta_A) + Sin(\theta_C)\, Cos(\theta_A)] \qquad \text{(Eq. 5)}$$

where θ_A is the actual position in electrical degrees. Applying trigonometric identity to Eq. 5, the torque of friction is

$$T_F = KI_o \, Sin(\theta_C - \theta_A) \qquad \text{(Eq. 6)}$$

Then, the calculated position error due to friction $(\theta_C - \theta_A) = \theta_{NRE}$ is,

$$\theta_{NRE} = +/-[Sin^{-1}(T_F/KI_o)] \text{ (electrical degrees)} \qquad \text{(Eq. 7)}$$

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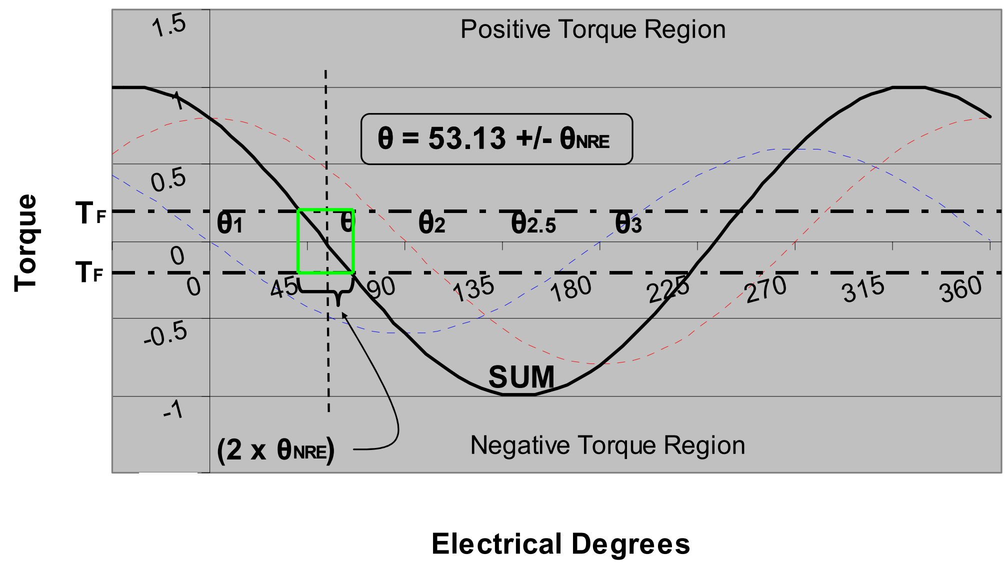

Fig. 7: Absolute Error: Motor Torque vs. Static Friction Torque

Repeatable

Repeatable Position Error is known as Relative Position Error. Motor Torque Harmonics, Drive Bias and Quantization effects are the common repeatable sources of error. Motor Torque Harmonics or 'torque ripple' is caused by electrical deviations and mechanical tolerances of components within the motor such as the windings, rotor, and air gap. Drive Bias is an unbalanced output of the phases from the drive, typically caused by unbalanced DAC components and gain offsets within the drive. Quantization Effects are deviations of the drive output from theoretically predicted performance. In other words, drive component non-linearity and unexpected DAC resolution will cause deviations of the ideal sine and cosine current output waveforms to the motor.

Each of the repeatable errors together generates non-ideal sine and cosine torque curves from the motor. The good news is these errors have predictable, repeatable influence on position error. However, each motor and each amplifier are unique with respect to these characteristics, thus evaluating the error from these sources becomes empirical per application, per axis.

Analysis: Effects on Performance

In culmination of the sources of error and their effects upon performance, let us expand on the sample system for an example analysis. In this example we will use Galil's SDM-20640 Microstepping Drive with a resolution of 1/64.

Step Motor, 200 steps/revolution
Nominal Current, I_o = 1.4A
Motor Torque Constant, K = 25 oz-in/A

Resolution = 12,800 counts/revolution = 0.028^o per count
Torque of Static Friction(Motor & Load), T_F = 5 oz-in

Non-Repeatable Error
Commanded move is 1000 counts

θ_o = 1000 = 28.125^o(Mechanical Degrees)

From Eq. 7 for Static Friction Error

θ_{NRE} = +/-[$Sin^{-1}(T_F/KI_o)$] = +/- 8.21^o (Electrical Degrees)

Converting Electrical Degrees to Mechanical Degrees

1 Step = 360^o/200 steps/rev = 1.8^o (Mechanical Degrees)
1 Step = 1.8^o = 90^o (Electrical Degrees)
$1.8^o/90^o$ = 0.02 (Mechanical Degrees per Electrical Degree)

Therefore,

θ_{NRE} x 0.02 = +/-0.164^o (Mechanical Degrees)

The sum of Non-Repeatable Error with resolution of 0.028^o per count is

$\boldsymbol{\theta_{NRE}}$ = $0.164^o/0.028^o$ = **+/- 5.9 counts error**

Thus, due to non-repeatable error alone, there is an absolute position error of 6 counts to be considered.

Repeatable Error
Commanded move is 1000 counts

θ_o = 1000 = 28.125^o (Mechanical Degrees)

Due to non-repeatable error, the absolute position was evaluated as

θ = 28.125 +/- 0.164^o or 27.96^o – 28.29^o

By empirical evaluation the repeatable relative position is between 27.90^o and 28.35^o.

Repeatable Actual Motor Position: θ = 27.90^o and 28.35^o.
Repeatable Position Error: θ_{RE} = +/- 0.06^o (Mechanical Degrees)

And, with resolution of 0.028^o per count

$\boldsymbol{\theta_{RE}}$ = $0.06^o/0.028^o$ = **+/- 2.1 counts error**

Therefore, due to repeatable sources of error, there is an additional 2 counts of position error to be considered. Overall, the accuracy of the system is within +/-6 counts, with a repeatability of +/-2 counts, not considering any axis mechanics external to the motor and drive. This indicates that even though the system has a resolution of 12,800 counts or, 0.028^{o} per count, the actual position could be +/-8 counts(microsteps) around the commanded position.

Conclusion

When considering the performance of an application, it is important to understand what the performance goal is. Some applications require absolute positional accuracy, whereas others are less concerned with accuracy and more with repeatability. It is equally important to consider the positional effects of other mechanical components associated with each axis. Lead screws, couplings and other mechanics will add to the repeatable error through coupling non-linearity, and to the non-repeatable error through tolerance.

The microstepping control method offers improved performance potential for stepper motor axes. However, resolution is no guarantee of actual position accuracy. Each axis has a variety of individual error sources which should be quantified and evaluated to predict actual microstep performance. For more information on step motor control, please see the following links.

Monitoring Step Motor Operation
http://galilmc.com/support/appnotes/optima/note2417.pdf

Backlash Compensation with Closed Loop Steppers
http://66.60.181.132/xnet/pdfcheckreg.aspx?location=servotrends&target=closedloopstepper

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