Industrial Circuits Application Note

Microstepping

This application note discusses microstepping and the increased system performance that it offers. Some of the most important factors that limit microstepping performance, as well as methods of overcoming these limitations, are discussed. It is assumed that the reader is somewhat familiar with stepper motor driving and the torque generation principles of a stepper motor. If not, chapter 1 and 2 of this book can be read to get the background information necessary.

What is microstepping

Microstepping is a way of moving the stator flux of a stepper more smoothly than in full- or half-step drive modes. This results in less vibration, and makes noiseless stepping possible down to 0 Hz. It also makes smaller step angles and better positioning possible.

There are a lot of different microstepping modes, with step lengths from 1/3-full-step down to 1/32-full-step—or even less. Theoretically it is possible to use non-integer fractions of a full-step, but this is often impractical.

A stepper motor is a synchronous electrical motor. This means that the rotor's stable stop position is in synchronization with the stator flux. The rotor is made to rotate by rotating the stator flux, thus making the rotor move towards the new stable stop position. The torque (T) developed by the motor is a function of the holding torque (T_H) and the distance between the stator flux (f_s) and the rotor position (f_r).

$$T = T_H \times sin(f_s - f_r)$$

where f_s and f_r are given in electrical degrees.

The relationship between electrical and mechanical angles is given by the formula:

$$f_{el} = (n \div 4) \times f_{mech}$$

where n is the number of full-steps per revolution.

When a stepper is driven in full-step and half-step modes the stator flux is rotated 90 and 45 electrical degrees, respectively every step of the motor. From the formula above we see that a pulsing torque is developed by the motor (see figure 1a, which also shows the speed ripple caused by the torque ripple). The reason for this is that $f_s - f_r$ is not constant in time due to the discontinuous motion of f_s.

Generating a stator flux that rotates 90 or 45 degrees at a time is simple, just two current levels are required I_{on} and 0. This can be done easily with all type of drivers. For a given direction of the stator flux, the current levels corresponding to that direction are calculated from the formulas:

$$I_A = I_{peak} \times sin(f_s)$$
$$I_B = I_{peak} \times cos(f_s)$$

By combining the I_{on} and 0 values in the two windings we can achieve 8 different combinations of winding currents. This gives us the 8 normal 1- and 2-phase-on stop positions corresponding to the flux directions 0, 45, …, 315 electrical degrees (see figure 2a).

If we have a driver which can generate any current level from 0 to 141% of the nominal 2-phase-on current for the motor, it is possible to create a rotating flux which can stop at any desired electrical position (see figure 2b). It is therefore also possible to select any electrical stepping angle—1/4-full-step (15 electrical degrees), 1/8-full-step or 1/32-full-step (2.8 electrical degrees) for instance. Not only can the direction of flux be varied, but also the amplitude.

From the torque development formula, we can now see that the effect of microstepping is that the rotor will have a much smoother movement on low frequencies because the stator flux, which controls the stable rotor stop position, is moved in a more-con-

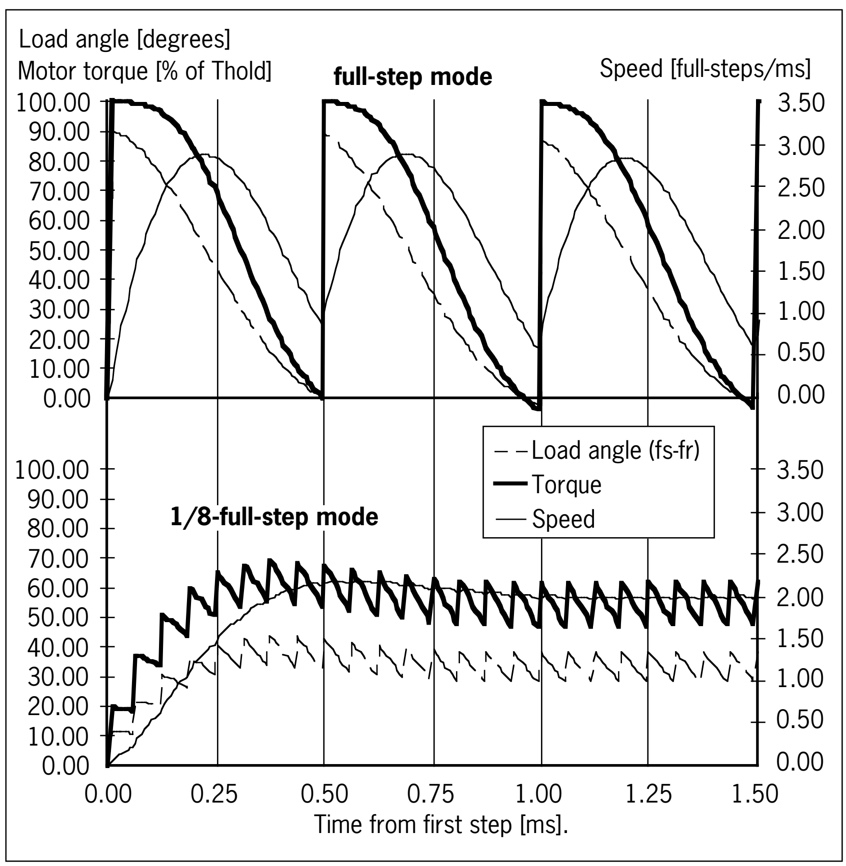

Figure 1. (A)—torque and speed ripple as function of load angle, full-step mode. (B)—torque and speed ripple as function of load angle, microstepping 1/8-full-step mode.

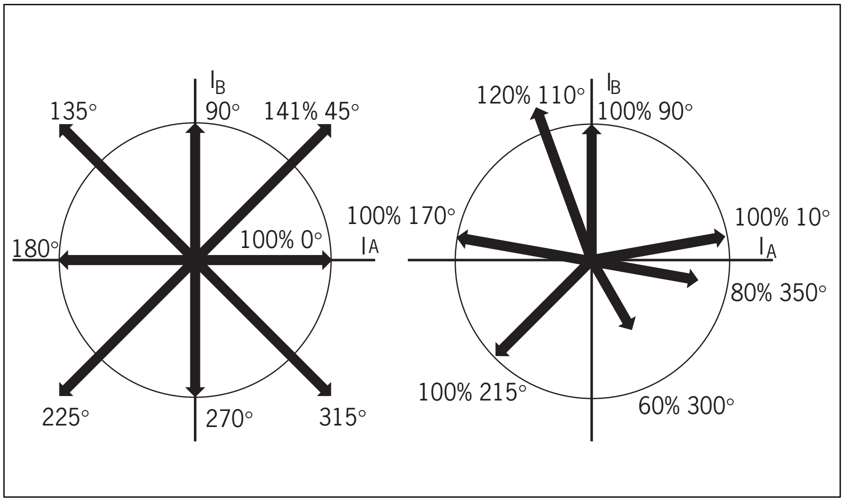

Figure 2. (A)—flux directions for normal half and full-step stop positions. Length is proportional to holding torque. (B)—microstepping flux directions. Direction and length are variable.

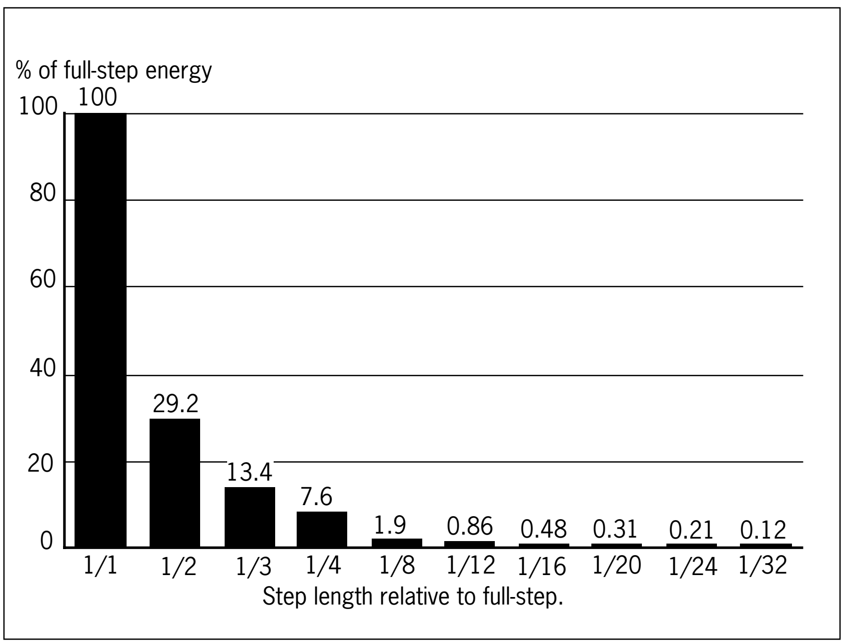

Figure 3. Relative excitation energy as function of electrical step length.

tinuous way, compared to full and half-step modes, (see figure 1b).

With frequencies above 2 to 3 times the system's natural frequency, microstepping has only a small effect on the rotor movement compared to full-stepping. The reason for this is the filtering effect of the rotor and load inertia. A stepper motor system acts as a low pass filter.

Why microstepping

In many applications microstepping can increase system performance, and lower system complexity and cost, compared to full- and half-step driving techniques. Microstepping can be used to solve noise and resonance problems, and to increase step accuracy and resolution.

Running at resonance frequencies

The natural frequency, F_0 (Hz), of a stepper motor system is determined by the rotor and load inertia, $J_T = J_R + J_L$ (Kgm^2), holding torque, T_H (Nm), (with the selected driving mode and current levels) and number of full-steps per revolution (n).

$$F_0 = (n \times T_H \div J_T)^{0.5} \div 4\pi$$

If the system damping is low there is an obvious risk of losing steps or generating noise when the motor is operated at or around the resonance frequency. Depending on motor type, total inertia, and damping; this problems can also appear at or close to integer multiples and fractions of F_0, that is: …, $F_0/4$, $F_0/3$, $F_0/2$, $2F_0$, $3F_0$, $4F_0$, … . Normally the frequencies closest to F_0 gives the most problems.

When a non-microstepping driver is used, the main cause of these resonances is that the stator flux is moved in a discontinuous way, 90 or 45 (full-step and half-step mode) electrical degrees at a time. This causes a pulsing energy flow to the rotor. The pulsations excite the resonance. The energy transferred to the rotor, when a single step is taken, is in the worst case (no load friction) equal to:

$$(4T_H \div n) \times [1 - \cos(f_e)]$$

T_H and n are as above and f_e = electrical step angle, 90 degrees for full-step, 45 degrees for half-step. This shows that using half-steps instead of full-steps reduce the excitation energy to approximately 29% of the full-step energy. If we move to microstepping 1⁄32-full-step mode only 0.1% of the full-step energy remains (see figure 3).

It appears that, by using microstepping techniques, this excitation energy can be lowered to such a low level that all resonances are fully eliminated.

Unfortunately this is only true for an ideal stepper motor. In reality there are also other sources that excite the system resonances. Never the less, using microstepping will improve the movement in almost all applications—and in many cases microstepping will alone give a sufficient reduction of the noise and vibrations to satisfy the application.

Extending the dynamic range towards lower frequencies

When running a stepper motor at low frequencies. in half- or full-step mode. the movement becomes discontinuous, shows a great deal of ringing, and generates noise and vibrations. The stepping frequencies where this happens are below the system's natural frequency. Here microstepping offers a easy and safe way to extend noiseless stepping frequencies down towards 0Hz. Normally it is not necessary to use smaller steps than 1⁄32-full-step. With this small electrical step angle the energy transferred to the rotor/electrical step is only 0.1% of the full-step energy, as described above, and is so small that it is easily absorbed by the internal motor friction—so no ringing or overshot is generated by the stepping (see figure 4). The deviation of the microstepping positions from a straight line is due to the use of uncompensated sine/cosine profiles.

Electronic "gearbox"

In some applications, where small relative movements or higher step resolution are required, microstepping can replace a mechanical gearbox. In many applications, this is often a better and less-complex solution—even if a larger motor has to be used. To get the best results in this type of application careful motor selection and development of customized sine/cosine profiles are recommended.

Improved step accuracy

Microstepping can also be used to increase stepper motor position accuracy beyond the manufacturer's specification. One way to do this is as follows. Design a microprocessor based microstepping system. Use the motor at 2-phase-on stop positions, $|I_a| = |I_b|$ (these are normally the most accurate rotor stop positions). Use a factory calibration process (manual or automatic) to store a correction value for each stop position on every motor used. The correction value is used to output "adjusted" full-step positions to the motor (see figure 5b). The adjusted positions have slightly changed current levels in the windings to compensate for the position deviations at the original stop positions (see figure 5a). This technique can be used when optimum step accuracy is the most important design criteria.

If this technique is used, the system has to use a rotor home position indicator to synchronize the rotor with the compensation profile.

System complexity

Even though the electronics for generating microstepping is more complex than electronics for full- and half-step-

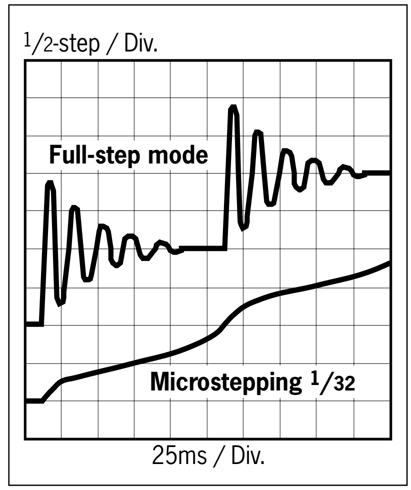

Figure 4. Rotor position as function of stepping mode.

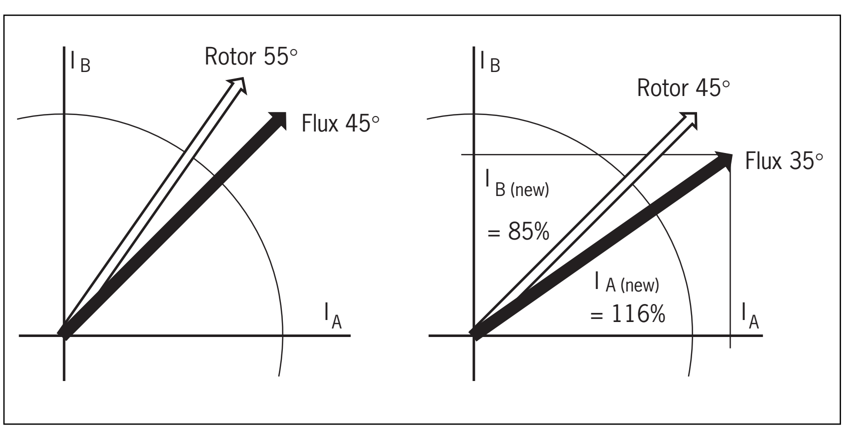

Figure 5. (A)—rotor and flux directions at original full-step position. (B)—rotor and flux directions at adjusted full-step position.

ping, the total system complexity including motor, gearbox and transmission is less complex and costs less in many applications. Microstepping can replace or simplify gearboxes and mechanics for damping of noise and vibrations. Also motor selection becomes easier and more flexible.

In a microprocessor,based microstepping application it is possible to use software and PWM-timers or D/A-converters internal to the microprocessor to replace an external microstepping controller to achieve lowest possible microstepping hardware cost. It is then possible to achieve the same hardware cost as in full- and half-step systems for similar motor sizes.

What affects microstepping performance

In theory, microstepping is quite simple, and theoretically, the technique solves all resonance, vibration and noise problems in a stepper motor system.

In reality, a lot of different phenomena arise which set limits for the system performance. Some are related to the driver and others to the motor. If a high-precision controller/driver combination such as PBM 3960 and PBL 3771 or equivalent are used, then the errors associated with the driver are negligible when compared with those associated with most available motors.

Step accuracy

In the manufacturers' stepper motor data sheets, the step accuracy is normally given. Step accuracy can be given absolute (±1.0 degree, as an example) or relative (±5% of one full-step). Normally step accuracy is only specified for 2-phase-on stop positions. (Here a 2-phase-on stop position means a position with the same current level in both windings. A position with different current levels, or none, in the windings is a microstep position.) This means that the manufacturer does not tell anything about the motor behavior when the motor is used in a microstepping application. Optimizing a motor for high full-step positioning accuracy and holding torque normally reduces microstepping accuracy.

One important effect of the 2-phase-on step accuracy is shown by the following example. Consider a microstepping design, using 1⁄32-full-step mode with a 7.5-degree PM-stepper motor. One microstep theoretically corresponds to $7.5 \div 32 = 0.23°$. For this type of motor a step accuracy of ±1 degree is common. This means that if the motor home position is calibrated at a randomly-selected 2-phase-on position (which can be positioned anywhere within ±1 degree from the theoretically-correct home position) the maximum deviation of the rotor at another 2-phase-on position can be $[1-(-1)] / 0.23 = 8.5$ microsteps from its theoretical position. This fact has to be considered when microstepping is used in applications were absolute positioning is essential. A technique to solve this problem is described previously under "Improved step accuracy".

Sine/cosine conformity

Most actual stepper motors do not have an ideal sine/cosine behavior (a stepper with idealized sine/cosine behavior will rotate with a absolute constant speed when a sine/cosine current pair is applied to the windings). Mainly due to varying air gap area, air gap distance and magnetic hysteresis the flux vector direction and magnitude—and therefore the microstepping stop positions and the microstepping holding torque—deviate from the ideal sine/cosine behavior. The deviations are dependent upon rotor and stator-tooth shape, and the type of material used in the construction.

Some motors are optimized for high holding torque or increased step accuracy at 2-phase-on stop positions. This can be done by shaping the teeth in such a way that a extra high flux is achieved at the 2-phase-on positions. This type of optimized motors should be avoided in microstepping applications because there large deviations from the sine/cosine behavior. The closer the motor conforms to the sine/cosine behavior the better performance in a microstepping application.

The deviations can be divided into two parts: of the amplitude of the flux vector (influences the microstepping holding torque), and of the direction of the flux vector (effects the microstepping stop positions).

Microstepping position ripple

When a stepper is used in a microstepping application, the microstepping stop positions are affected by the sine/cosine conformity. The difference between the theoretical and actual microstepping stop positions is called microstepping position ripple. It is defined as the average deviation, for all full-step cycles over a full revolution, of the actual microstep stop positions from the theoretical, when a sine/cosine current wave form is applied to the motor windings (see figure 6). The microstepping position ripple is a median value over the whole revolution. This means that it is not a function of the normal 2-phase-on step accuracy. To calculate the total microstepping accuracy, the microstepping position ripple has to be added to the 2-phase-on accuracy.

The effect of the microstepping position ripple is that, when a motor is driven with an uncompensated sine/cosine profile, the rotor movement will show a varying speed over the full-step cycle—in other words, the microsteps will vary in length. Microstep lengths from ½ to 3 times the nominal are not uncommon when a microstep length of 1⁄32-full-step is used (see figure 7).

In microstepping applications, this is most common phenomena that excites the systems resonances.

Microstepping holding torque ripple

The magnitude of the magnetic flux will also deviate from the theoretical value when microstepping is applied to a stepper motor. This is referred to as microstepping holding torque ripple. The nominal holding torque is theoretically independent of the flux direction when the motor is driven with a sine/cosine current wave form. The theoretical holding torque is calculated from the formula:

$$T_H = k \times (I_A^2 + I_B^2)^{0.5}$$

If I_A and I_B are sine/cosine pair then T_H is independent of flux direction.

The magnitude of the microstepping holding torque ripple, which is a function of the nominal stator and rotor-tooth geometry, is normally in the range 10 to 30% of the nominal 2-phase-on holding torque. Most motors are optimized for highest holding torque at the 2-phase-on positions (see figure 8).

The microstepping holding torque ripple is an average value for all full-step cycles over one full revolution and should not be confused with the motor-tolerance-dependent 2-phase-on holding torque ripple. When a stepper is stopped at different 2-phase-on positions the holding torque normally differs up to ±10% of the nominal holding torque. These variations are caused by mechanical tolerances in the rotor/stator geometry of the motor and would be zero for a geometrically correct motor.

Hysteresis

The stop-position hysteresis of a stepper motor is mainly affected by the magnetic hysteresis, but also partly by the friction of the rotor bearing. If we measure the microstep stop positions, first by rotating the motor in CW direction and then in the CCW direction the hysteresis will clearly show (see figure 6).

The magnetic flux in the air gap is theoretically proportional to the number of turns in the winding (n) and the winding current (I).

$$F_A = k_f \times n \times I$$

Because of the hysteresis of the magnetic materials in the rotor and stator flux path, this is not quite true. When hystereses are involved, the present flux is a function of the present winding current and the flux history (see figure 9). The H value is directly proportional to the winding current, but to determine the flux it is also necessary to know the previous H-values (the flux history). In applications where positioning accuracy is important, it is some times necessary to use an over-shot movement so as to always have the hysteresis on the same side and thereby not create any additional positioning error.

In a high-resolution microstepping application, the hysteresis can be several times the nominal microstep length.

When the total positioning accuracy of a stepper motor system is calculated, it is important to know if the hysteresis is included in the step accuracy given in the motor data sheet.

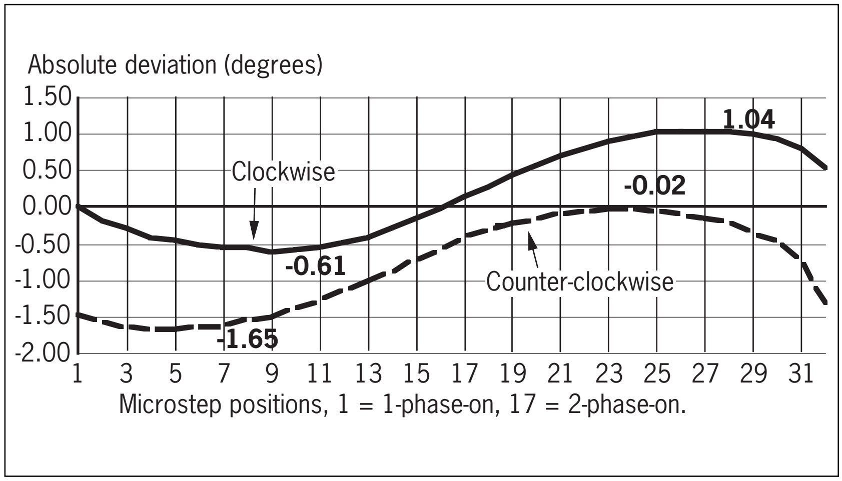

Figure 6. Microstepping position ripple for a 57mm 7.5 degree PM stepper. CW ripple = 1.04 - (-0.61) = 1.65 degrees = 22%.

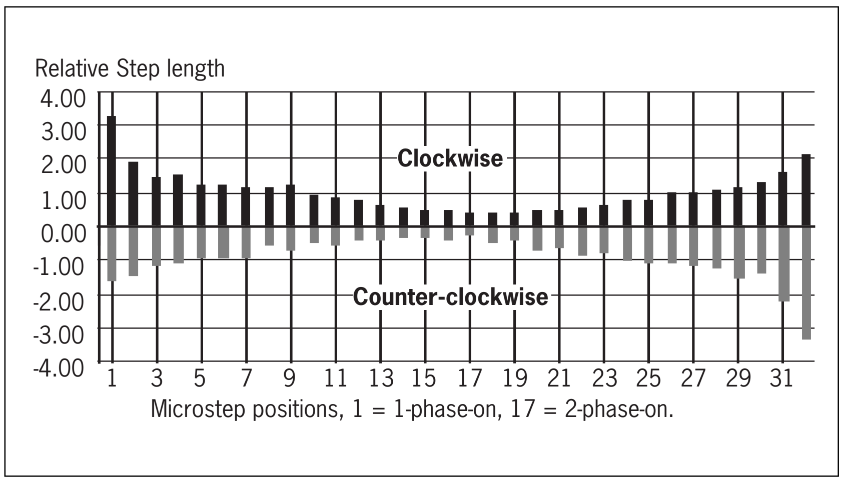

Figure 7. 57mm PM-stepper relative microstep length as function of stop position, 1/32-full-step mode.

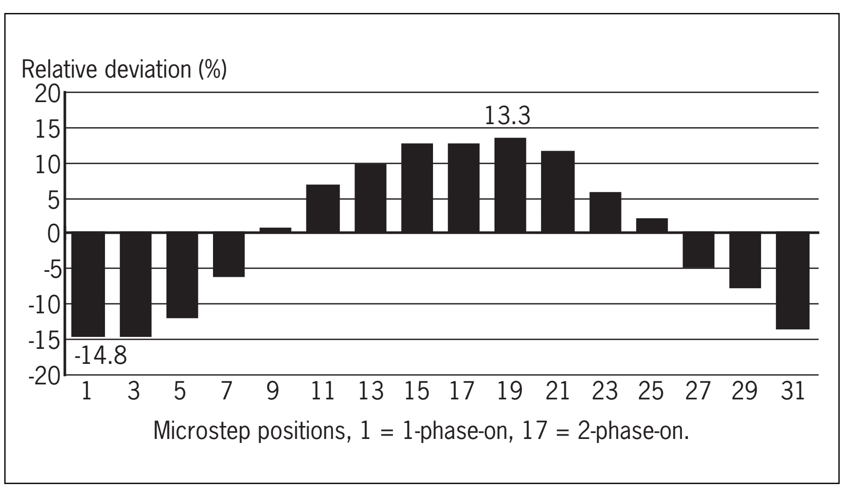

Figure 8. Microstepping holding torque ripple for a 57mm PM stepper. Ripple = 13.3 - -14.8 = 28.1%.

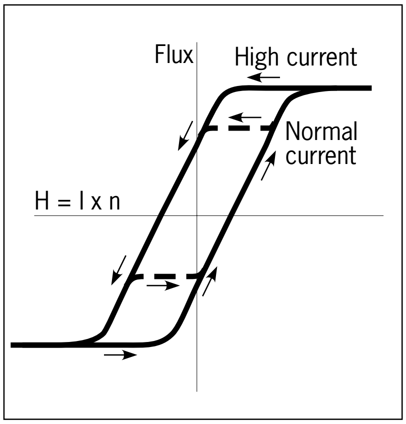

Figure 9. Flux as function of flux history and H-value when two different current levels are applied to the winding.

Torque ripple
When the stepper motor is stepped in full- or half-step mode, there will be a pulsing torque developed by the motor. This pulsing torque has the same mean value as the load friction torque, but can in some applications have a peak value 20 or more times as high as the average value. This is the main cause of noise and resonances in stepper motor systems. This phenomena is also known as torque ripple. In an ideal stepper motor, the torque ripple is a function of the holding torque, the stepping method, and the load angle (f_l). The load angle, or rotor lag, is defined as the median deviation between the electrical stator flux and the rotor position measured in electrical degrees.

In a real application the torque ripple is also affected by the sine/cosine conformity of the stepper and driver used.

When microstepping is used to reduce noise in a stepper application, it is important to know the dominant source that excites the resonances. The formulas below show that a high precision controller driver combination such as PBM3960 and PBL3771 reduces the errors associated with the driver/controller to a negligible level compared to most motors.

Microstep-length-related torque ripple
If we drive an ideal stepper motor with an ideal and continuous sine/cosine current wave form then the torque ripple will be zero. If we instead use sine/cosine microstepping, the torque ripple will be a function of the motor holding torque (T_H) the microstep length (f_e) and the average load angle (f_l). This assumes that the rotor speed is constant—which is a good approximation for a simple model. We can now calculate the torque ripple associated with the microstepping length.

$$T_{Rfe} = T_H \times \frac{f_e \times \pi}{180} \times cos(f_l)$$

f_e and f_l given in electrical degrees.

Motor sine/cosine conformity related torque ripple
In an actual design, the motor is not ideal and, as mentioned above, we have two types of deviations from the sine/cosine behavior. Let us now calculate the torque ripple associated with these deviations. For an approximation, we still consider the rotor speed as constant.

First, assume the microstepping position ripple equals zero and drive the motor with ideal sine/cosine current curves (no driving-mode-related torque ripple). We can now calculate the torque ripple associated with microstepping holding torque ripple (T_{mhtr}).

$$T_{Rmhtr} = T_{mhtr} \times sin(f_l)$$

Next assume the microstepping holding torque ripple equals zero and, still using ideal sine/cosine current wave forms, calculate the torque ripple associated with the microstepping position ripple (f_{mpr}).

$$T_{Rmpr} = T_H \times [(f_{mpr} \times \pi)/180] \times cos(f_l)$$

f_{mpr} and f_l given in electrical degrees.

Motor tolerance related torque ripple
The 2-phase-on step accuracy and holding torque variations of the motor also generate a torque ripple. Usually the effect from these errors can be ignored because they are not cyclic but random, or if cyclic not periodic on full-step cycles. This makes the risk that these errors will excite the system resonance lower. If necessary, the torque ripple associated with these errors can be calculated in a similar way to the microstepping errors related to the motor. To minimize these type of errors use a high quality motor with small internal geometric tolerances.

Driver related torque ripple
When we use an non-ideal driver, the driver will also contribute to the torque ripple. This contribution can be separated into one microstepping position ripple and one microstepping holding torque ripple, in the same way as for the motor. Depending on the type of motor and driver used, either the driver or motor errors will dominate. If Ericsson's high-precision microstepping controller and driver are used, then the errors associated to the driver normally can be ignored (both the driver microstepping position and holding torque ripple are less than 1%). If other types of drivers, or if high-precision microstepping motors, are used then the best way of estimating the total system (driver and motor) error is to measure the microstepping holding torque ripple and microstepping position ripple of the motor and driver combination together. If the driver-related error can not be ignored, it can be calculated in the same way as the errors related to the motor. One part concerning the flux vector position and one concerning the magnitude of the flux.

Comparing the different torque ripple sources
We can now compare the magnitude of the torque ripple generated by the different sources. As we can see from the formulas above, we also have to take the average load angle (f_l) into consideration. This means that, depending on whether we have a high or low friction load in the system, the different error mechanisms will generate different amounts of torque ripple. We will study three different cases. First, with zero load angle—this system can be a good approximation for many low-friction-load systems. Second, 12-degree load angle (21% of available torque used)—this is a normal value for many medium performing systems. Third, a 49-degrees load angle (75% of available torque used)—this is close to the maximum practically-available torque under the best driving conditions and can be used for

a high performance motor drive. Table 1 compares the torque ripple from the different sources under different conditions, also torque ripples calculated for 6- and 30-degree load angles.

Measuring microstepping performance

To develop compensated sine/cosine current profiles in a systematic manner, we need to measure the microstepping position ripple, and in some applications, the microstepping holding torque ripple.

Measuring microstepping position ripple
To measure the stop position ripple use a microstepping controller/driver (Ericsson TB307I for an example)—make sure that the same chopping voltage, current levels, current decay mode and chopping frequency are used as the in the final application. Use a high-precision miniature coupling to fix a high-precision, low-friction, optical encoder to the stepper motor shaft to measure the rotor stop positions. If possible, use two couplings in series separated by a 50 – 100 mm axle (see figure 10).

Be careful with the mechanical set-up—misalignment of the motor and encoder shafts will affect the measurement accuracy.

First, microstep the motor in the CW direction for at least one full-step distance. Continue in the CW direction to the next 1-phase-on stop position. Reset the rotor position measurement. Move the rotor one microstep in the CW direction. Note the new stable stop position. Continue in this way until the stator flux has moved 4 full-step positions (360 electrical degrees) in the CW direction. Now rotate the flux an additional full-step distance without noting the stop positions (this is to allow the flux hysteresis to build up on positions not measured). Change the direction to CCW and microstep the flux back to the last measured flux stop position, note the CCW stop position. Continue microstepping the motor in the CCW direction and note all the CCW stop positions.

Calculate the CW and CCW deviations from the theoretical stop positions. Plot the deviations in a graph.

From the graph, we can read the hysteresis and the CW and CCW microstepping position ripple as functions of the flux direction for the microstep positions (see figure 11). Observe the cyclisity, the deviation repeats every 90 electrical degrees. This is a result of the sine/cosine 90-degree symmetry. Calculate the average deviation of the four cycles to get a more-accurate measurement result. The curve in figure 6 is calculated from figure 11 in this way. This data is the input for calculating compensated sine/cosine profiles. To get even-more-accurate data the deviations can be measured for a integer multiple of 4 full-step cycles. For the best results, use all the full-step cycles in one whole revolution.

Measuring microstepping holding torque ripple
To measure the holding torque ripple as a function of the microstepping stop positions, a microstepping driver and a torque watch or torque sensor are needed. Measure the holding torque as a function of the flux direction (see figure 12). Calculate the torque ripple from the measurements by subtracting the average value. Figure 8 is calculated from figure 12 in this way. The microstepping position ripple is a full-step cyclic function. For best accuracy measure as many cycles as possible. For a 3.6 degree stepper, there are 25 stable stop positions with the same flux direction. It is possible to measure all of them without changing the flux direction. Make sure you measure the holding

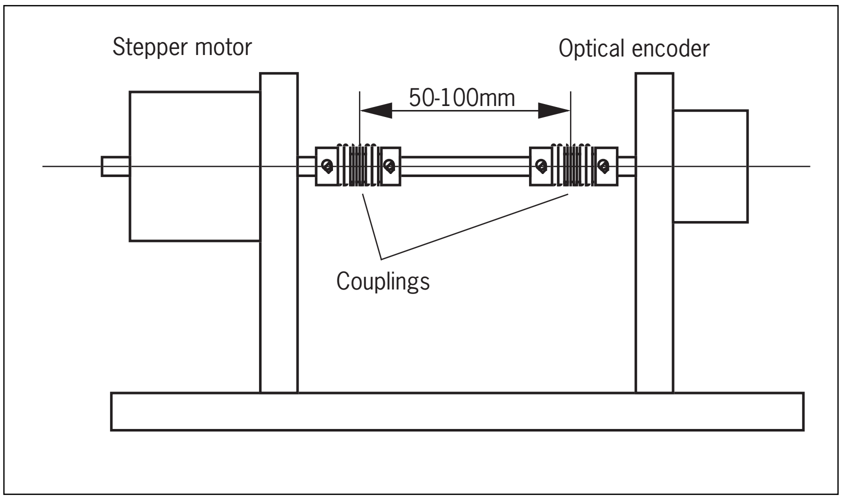

Figure 10. Suggested set-up for measuring microstepping position ripple.

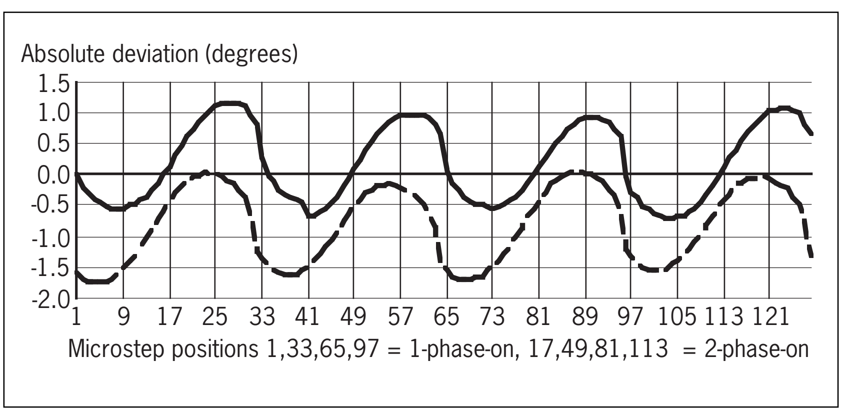

Figure 11. Microstepping position ripple for 4 full-step cycles for a 57mm 7.5 degree PM stepper.

Table 1. Absolute torque ripple as function of driving conditions and different torque ripple sources.

Conditions		Torque ripple [mNm]				
Mean load angle [degrees]		0	6	12	30	49
Friction torque [% of T_{hold}]		0	10	21	50	75
Driver mode	*microstepping length*					
1/1-stepping	90.0	157	156	154	136	103
1/2-stepping	45.0	79	78	77	68	52
1/8-stepping	**11.3**	**20**	**20**	**19**	**17**	**13**
1/16-stepping	5.6	10	10	10	9	6
1/32-stepping	2.9	5	5	5	4	3
Motor microstepping holding torque ripple						
5% (5mNm)	0.05	0	1	1	3	4
10% (10mNm)	0.10	0	1	2	5	8
20% (20mNm)	0.20	0	2	4	10	15
30% (30mNm)	**0.30**	**0**	**3**	**6**	**15**	**23**
40% (40mNm)	0.40	0	4	8	20	30
Motor microstepping position ripple						
5% (0.38 deg.)	*0.05*	*8*	*8*	*8*	*7*	*5*
10% (0.75 deg.)	0.10	16	16	15	14	10
20% (1.5 deg.)	0.20	31	31	31	27	21
30% (2.25 deg.)	**0.30**	**47**	**47**	**46**	**41**	**31**
40% (3.9 deg.)	0.40	63	62	61	54	41
Driver microstepping holding torque ripple						
1% (1mNm)	**0.01**	**0**	**0**	**0**	**1**	**1**
2% (2mNm)	0.02	0	0	0	1	2
5% (5mNm)	0.05	0	1	1	3	4
10% (10mNm)	0.10	0	1	2	5	8
Driver microstepping position ripple						
1% (0.9 el. deg.)	**0.01**	**2**	**2**	**2**	**1**	**1**
2% (1.8 el. deg.)	0.02	3	3	3	3	2
5% (4.5 el. deg.)	0.05	8	8	8	7	5

Values are calculated for a 7.5 degree 57mm PM-motor with 100mNm holding torque. Typical values are shown in bold type.

torque in the same mechanical direction for all stop positions and, if only a few positions are measured, measure the same mechanical stop position at all flux stop positions to get the best measurement accuracy.

The results of these measurements are the input data for calculating microstepping holding torque compensated sine/cosine current profiles.

Designing compensated sine/cosine profiles

From the discussion above, we see that there are many motor-specific parameters that affect the microstepping performance in an application. In fact, if no actions are taken, the motor will always limit the performance. Theoretically, microstepping is done with sine/cosine current wave forms, but the flexibility of the PBM 3960 microstepping controller allows for easy modification of the current profile. Adding a microprocessor to the control also makes handling of hysteresis and CW/CCW-unsymmetry a matter of software.

The sine/cosine conformity is mainly dependent upon the rotor/stator geometry and the material used in the construction. For most motors, the deviations among the individuals are relatively small compared to the average deviations from the theoretical values. This makes designing compensated sine/cosine current profiles an effective way of improving microstepping performance in a specific design.

Microstepping position ripple compensation

The compensated sine/cosine profile is calculated from the measured microstepping position ripple profile. Use the measured deviations at the different applied flux directions to interpolate new flux directions with zero deviation. Use these new flux directions to build the compensated sine/cosine profile. Now measure the microstepping position ripple with the compensated current profiles driving the motor. If necessary make further modifications to the current profile; and repeat the measurement until an acceptable result is obtained. Figure 13 shows the microstepping position ripple for the motor measured in figure 11 and 6 after applying compensated sine/cosine profiles to the motor. In figure 14 the full-step cycle average value is plotted. The compensated curve is a "first try", to get a even better result the procedure can be repeated with the new measured data as input.

If the application requires bidirectional rotation of the rotor, calculate different compensated profiles for the CW and CCW directions. In some applications it is possible to use the average CW and CCW deviation curve for both CW and CCW directions. Depending on the motor hysteresis level, this gives a somewhat less precise compensation.

The above method gives the best result when the rotor speed is low. When the speed is increased, the flux history of the motor is influenced by the rotor EMF, so the measured stop positions are not the correct ones. In these cases an experimental compromise between the uncompensated sine/cosine profile and the position-ripple-compensated profile normally gives the best result.

Holding torque ripple compensation

Normally, in applications were the friction load torque is low compared to the motor holding torque, no compensation for microstepping holding torque ripple is necessary (see table 1). The primary source of resonance excitation is the microstepping position ripple.

If compensation for holding torque is required it can be applied alone or together with the stop position compensation.

Use the measured microstepping-dependent holding torque to calculate the new current levels.

$$I_{new} = I_{old} \times (T_{Hnom} \div T_{Hmeasured})$$

This is applied to both winding currents.

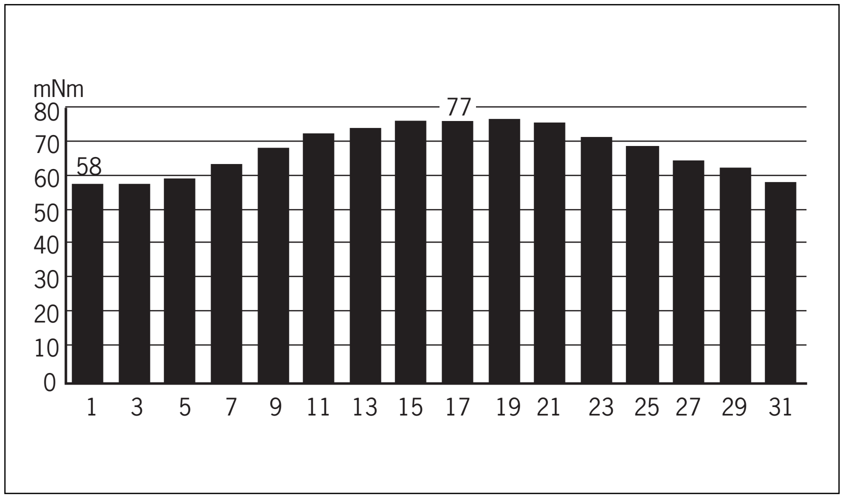

Figure 12. Microstepping holding torque for a 57mm PM stepper.

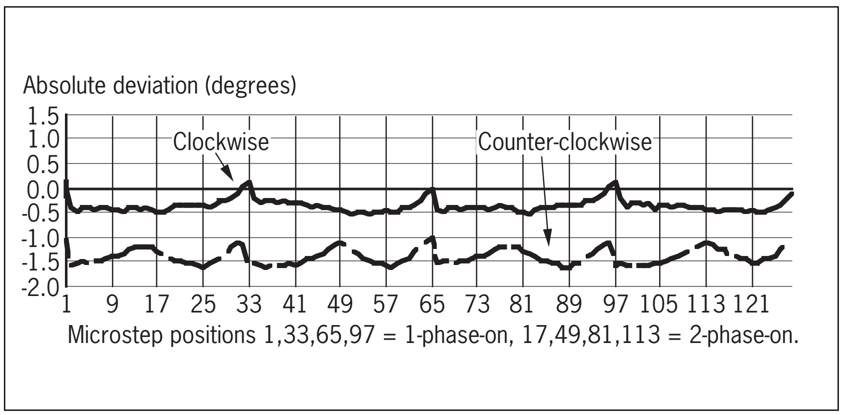

Figure 13. Sine/cosine CW compensated microstepping position ripple for 4 full-step cycles for a 57mm 7.5 degree PM stepper.

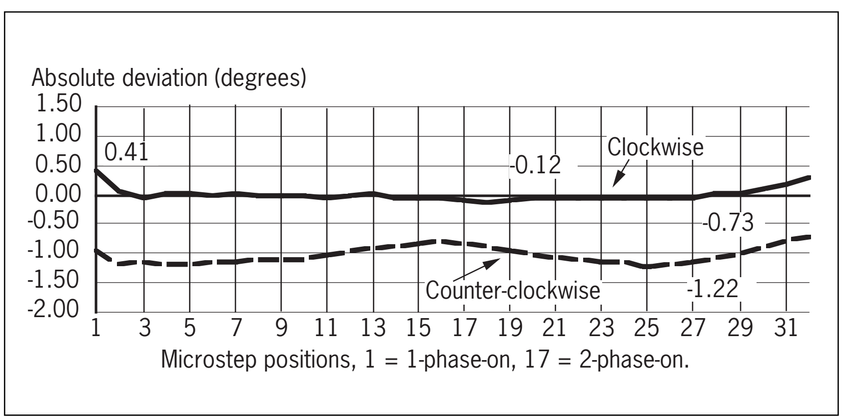

Figure 14. Sine/cosine compensated microstepping position ripple for a 57mm 7.5° PM stepper. CW ripple = 0.41 - -0.12 = 0.53 degrees =7% compared to 22% for uncompensated.