How to Reduce Audible Noise in Stepper Motors

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ABSTRACT

Stepper motors are known to generate audible noise as they operate, which is undesirable for many applications. Traditional stepper motor drivers with fixed-percentage mixed decay current chopping and low levels of microstepping greatly contribute to the noise. But features such as smart tune technology and high microstepping can help lower the audible noise significantly. The goal of this application report is to explain how specific motor driver features can reduce the audible noise for a wide variety of stepper motor systems and applications.

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Trademarks

1 Introduction

Stepper motors are used in a wide array of applications such as printers, projectors, textile machines, stage lighting, industrial automation, electronic point of sale, automotive headlight, and head-up display. A stepper motor moves in discrete steps as defined by a step angle during its rotation. It has two electrical current windings and each winding can be controlled with an H-Bridge. As shown in Figure 1, the stepper motor driver applies current waveforms approximating a sine wave (blue) into one coil and a cosine wave (red) into the other. One quadrant (90°) of the current waveforms corresponds to the stepper motor rotation by one step angle, which is 1.8° for most hybrid stepper motors used today.

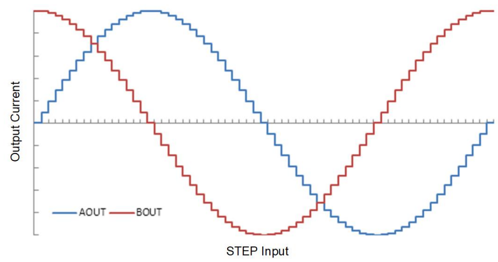

Figure 1. Microstepping Current Waveform

Most stepper motor drivers limit current by "chopping" their drive output at some frequency, called the PWM frequency. During PWM current chopping, the H-bridge is enabled to drive through the motor winding until the PWM current chopping threshold is reached. This is shown in Figure 2, Item 1.

Once the chopping current threshold is reached, the H-bridge can operate in two different states, fast decay or slow decay. In fast decay mode, once the PWM chopping current level has been reached, the H-bridge reverses state to allow winding current to flow in a reverse direction. The opposite FETs are turned on; as the winding current approaches zero, the bridge is disabled to prevent any reverse current flow. Fast decay mode is shown in Figure 2, item 2. In slow decay mode, winding current is re-circulated by enabling both of the low-side FETs in the bridge. This is shown in Figure 2, Item 3. Most legacy stepper drivers feature a fixed-percentage mixed decay scheme, where the decay mode is fast decay for a fixed percentage of the OFF time, and slow decay for the rest of the OFF time.

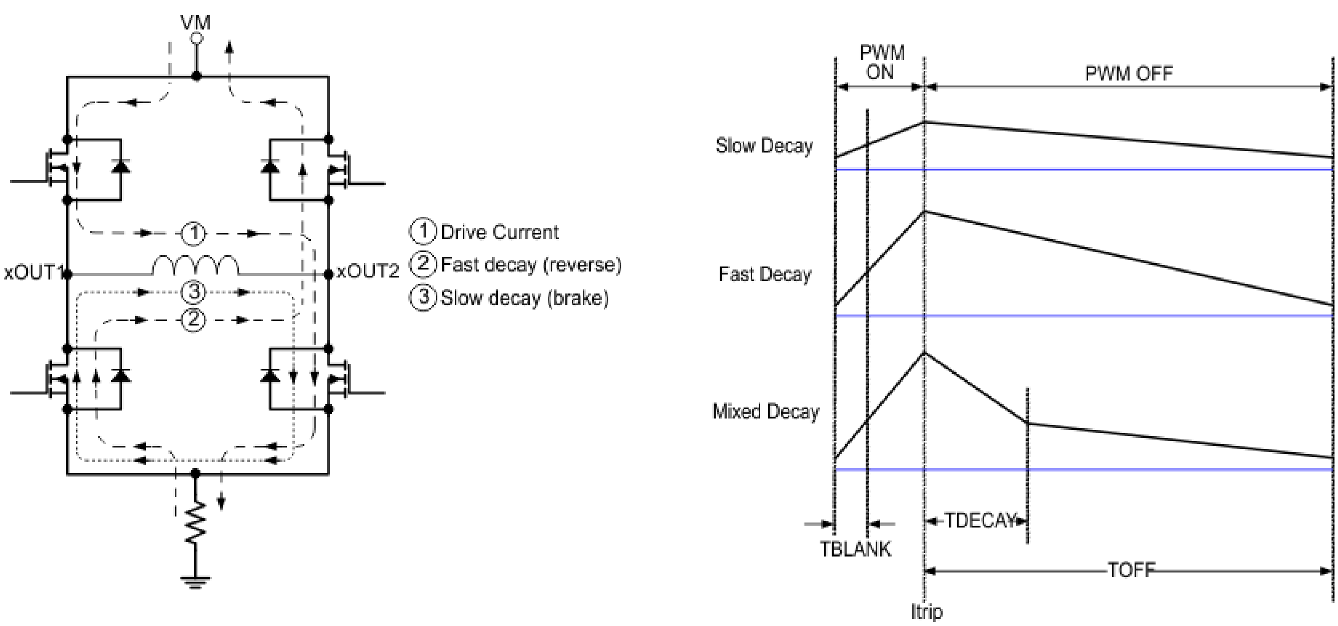

Figure 2. Decay Modes

With traditional slow, fast and mixed decay modes, stepper motors can be known to hum and whine as they operate. In most applications, the audible noise can annoy users and might warrant expensive noise suppression methods, such as rubber isolators, which do not completely eliminate the noise. For example, household or office printers and 3D printers have multiple stepper motors within them, and the noise from the motors can break concentration of their users. Higher quality stepper motor drivers that can reduce the motor noise go a long way towards user satisfaction. Another example is electric vehicles, which are generally quiet due to the absence of an internal combustion engine, and lowering the noise level from stepper motors used in headlight leveling helps to achieve a overall quiet cabin.

In the following sections, we will discuss the various sources of noise in stepper motors and how different stepper motor driver features can alleviate most of that noise.

2 Details of the Test Setup

In this application report, several measurements were taken to demonstrate the effectiveness of different settings in stepper motor drivers in reducing the motor noise. Sound pressure level (SPL) was used as one method of measurement. SPL is the measurement of local pressure deviation from the ambient pressure caused by a sound wave. SPL is represented graphically with sound in decibels (dB) versus frequency. To obtain the SPL plots shown in this application report, a microphone and a stepper motor driven by a DRV8424 driver were placed inside an acoustic chamber. The audible noise from the stepper motor was recorded at various operating conditions to obtain SPL plots. Figure 3 shows a picture of the microphone inside the chamber. The details of the setup are as follows:

- The motor was securely mounted on rubber to minimize extra vibrations.
- The stepper motor is rated for 2.3 A, has 1.8° step angle, 1.9 mH inductance and 0.93 Ω resistance.
- A calibrated USB microphone was used for recording the noise.
- First, a few seconds (approximately 5 sec) of ambient noise was captured to use as reference.
- Then, a few seconds (approximately 5-10 secs) of audio was recorded while the motor was spinning.
- The files from the audio recording were imported to a software to obtain the SPL plots.

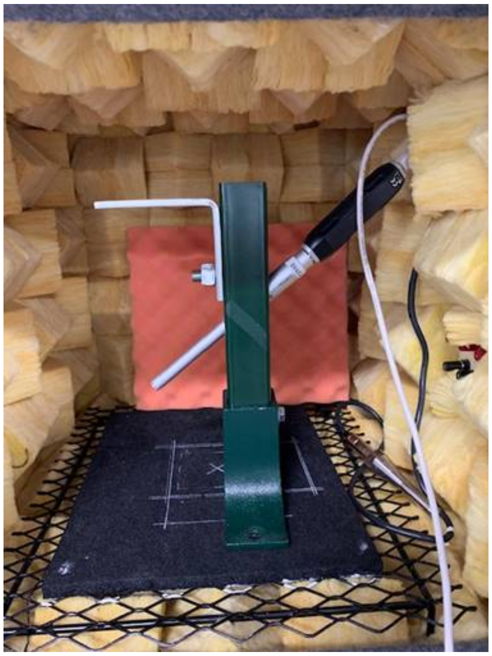

Figure 3. Audible Noise Measurement Setup

3 Sources of Noise in a Stepper Motor

The amount of audible noise from a stepper motor depends on the type of motor and the operating conditions. Stepper motor noise has been described as a high-pitched whine, a hissing noise or even a deflating tire. Human audible frequency range is generally considered as 20 Hz to 20 kHz, but the human ear is most sensitive to frequencies between 2 kHz and 15 kHz. Permanent magnet and hybrid stepper motors are generally quieter, whereas variable reluctance stepper motors are the noisiest.

The sources of noise coming out of a stepper motor can be broken into three main categories: magnetic, mechanical, and electrical.

3.1 Magnetic Noise

A property of ferromagnetic materials is magnetostriction, which causes magnetic materials to expand or contract in response to a magnetic field. The molecular dipoles and magnetic field boundaries shift in response to the magnetic field, changing length slightly in the direction of the applied field, as shown in Figure 4. In a stepper motor, magnetostriction deforms the iron and pulls the rotor and stator teeth toward each other in the air gap, causing audible noise.

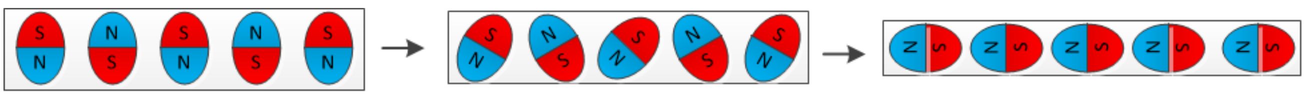

Figure 4. Molecular Dipoles Changing With Applied Magnetic Field

For stepper motors, the audible sound of magnetostriction manifests itself as an intense low pitch hum. Stepper motors operating at low speeds show the worst effects of magnetostriction. Thus, magnetostriction has the worst noise effects for motors used in laser printers and copiers due to generally low motor operating speeds.

Noise resulting from magnetostriction can not be completely eliminated, but it is known that certain types of metals are more prone to magnetostriction than others. There are special materials that compromise between magnetostriction and core losses to achieve the best performance for a given application.

3.2 Mechanical Noise

Mechanical noise is caused by the physical components in the structure of the stepper motor. Common examples contributing to noise include unsecured mounting structures, bent shafts, and loose or no bearings. All of these examples cause unnecessary vibrations and resonant frequencies to appear. Other mechanical noise factors include motor housing, balance of rotor, and bearing choice.

The motor housing structure has a significant effect on high speed motor applications. If the rotor is out of balance, there will be a spike in frequency directly related to speed of the motor. Electric motors use serval types of bearings: sliding sleeve bearings or rolling bearings. Sleeve bearings are generally considered to be quiet bearings. A properly lubricated sleeve bearing will only produce very high noise frequencies due to the bearing and shaft finish. Rolling bearings are generally considered to be noisy and have many factors that could lead to a noisy outcome.

Most mechanical noise can be minimized by stiffening the mounting structures and choosing noise dampening materials - such as mounting the motors in sound absorbing materials like rubber, balancing the rotor, and using properly maintained bearings.

3.3 Electrical Noise

There are various electrical sources of audible noise for a stepper motor, detailed in the subsequent sections. Unlike magnetic and mechanical noise, proper selection of the stepper motor driver can lead to the reduction of the electrical noise.

3.3.1 Effects of Current Ripple and Decay Mode

The smoothest and quietest 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 in the motor, which manifests as vibration and noise during operation. To reduce the ripple and therefore audible noise, it is recommended to operate a stepper motor on slow decay mode whenever possible, instead of fast or mixed decay.

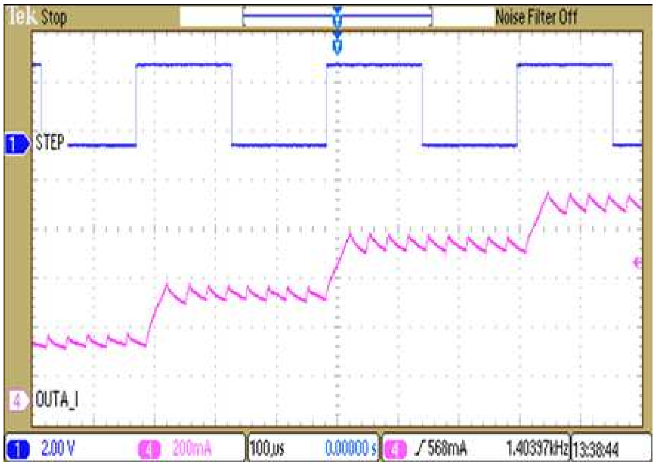

Figure 5. Microstepping Current vs STEP Input, Slow Decay

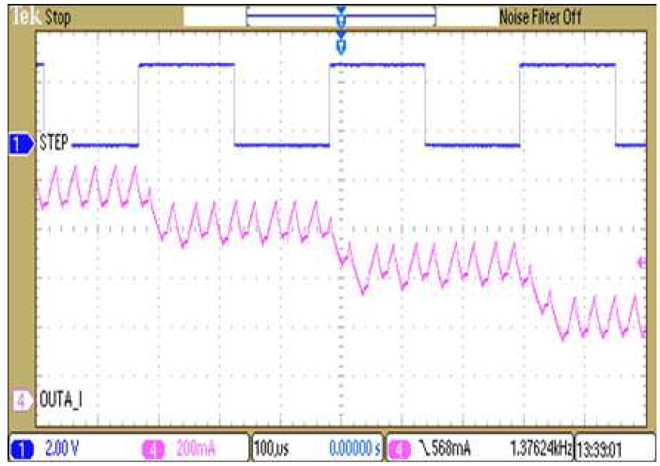

Figure 6. Microstepping Current vs STEP Input, Mixed Decay

Figure 5 and Figure 6 show the current ripple in slow decay and fixed-percentage mixed decay, respectively, for the same operating conditions. Current ripple is roughly 50 mA with slow decay, but close to 200 mA when the decay mode is changed to traditional mixed decay with 30% fast 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, as shown in Figure 7 and Figure 8 for mixed decay and slow decay respectively. Therefore, a slow decay mode which can follow the ideal waveform at all conditions is the ideal candidate for reducing audible noise from stepper motors.

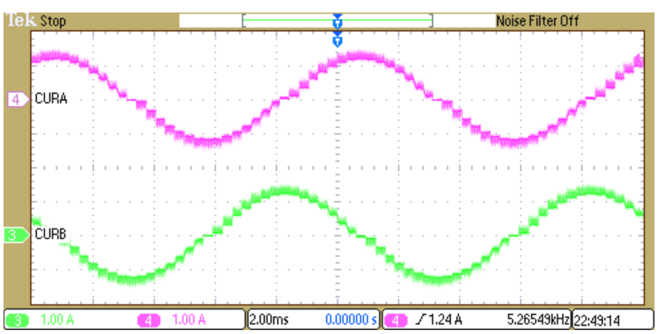

Figure 7. 30% Mixed Decay on Increasing and Decreasing Steps

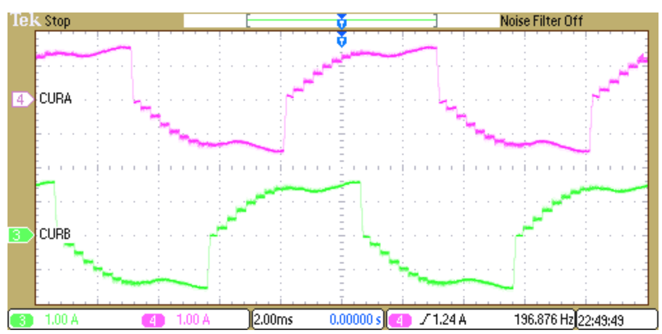

Figure 8. Slow Decay on Increasing and Decreasing Steps

The smart tune Ripple Control (STRC) mode featured in several stepper motor drivers from Texas Instruments is one such slow decay scheme. As shown in Figure 9, smart tune Ripple Control operates by setting an I_{VALLEY} level alongside the I_{TRIP} level. When the current level reaches I_{TRIP}, instead of entering slow decay until the t_{OFF} time expires, the driver enters slow decay until I_{VALLEY} is reached.

Therefore, this mode allows much tighter regulation of the ripple current than traditional mixed decay schemes. In this mode, t_{OFF} varies depending on the current level and operating conditions. On decreasing steps, smart tune Ripple Control automatically switches to fast decay to reach the next step quickly - which enables it to follow the ideal sinusoidal current waveform at all speeds.

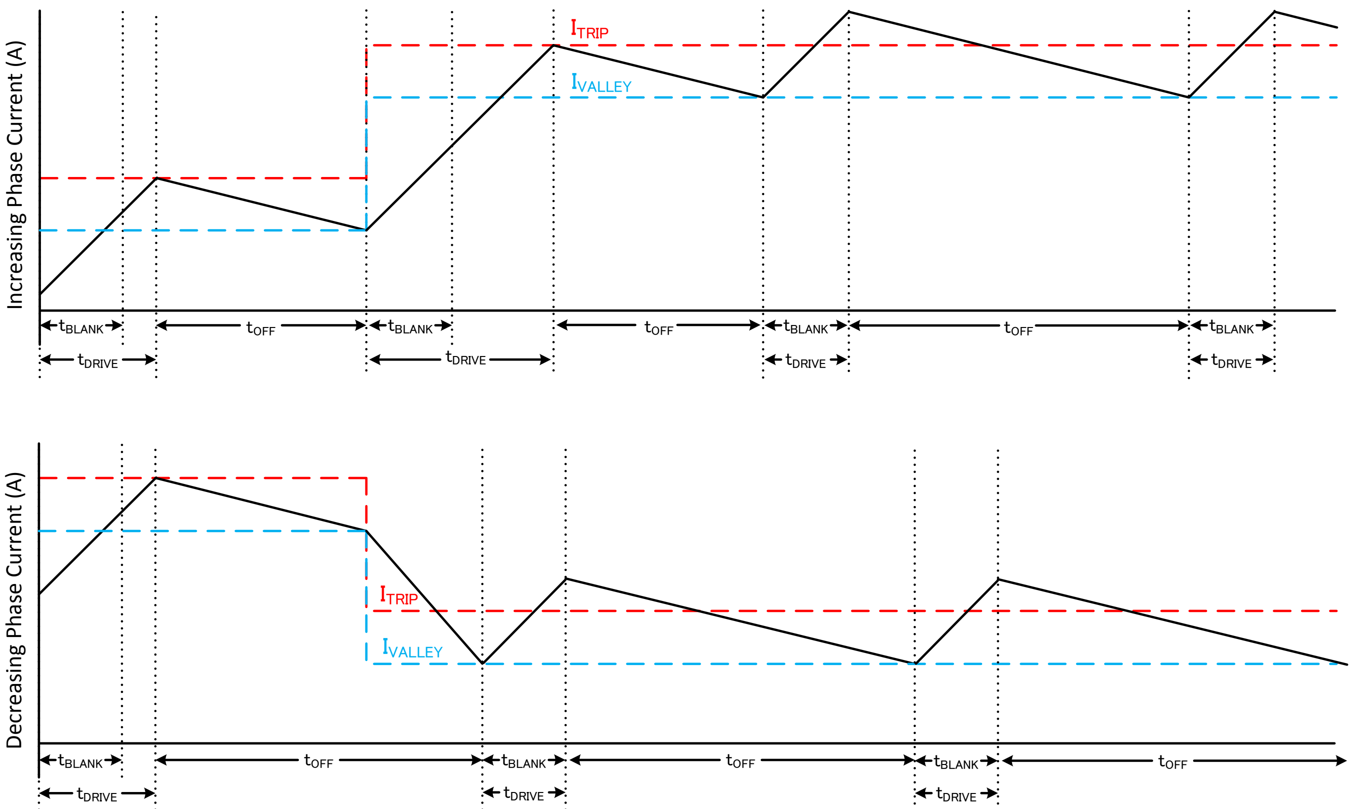

Figure 9. Smart tune Ripple Control Decay Mode

Table 1 lists various stepper motor drivers which feature the smart tune Ripple Control decay mode.

Table 1. Stepper Motor Drivers With Smart Tune Ripple Control

Device	Operating Supply Voltage Range	Full-Scale Current	$R_{DS(ON)}$ (HS + LS)	Microstepping
DRV8428	4.2 - 33 V	1 A	1500 mΩ	1/256
DRV8899-Q1	4.5 - 45 V	1 A	1200 mΩ	1/256
DRV8889-Q1	4.5 - 45 V	1.5 A	900 mΩ	1/256
DRV8436	4.5 - 48 V	1.5 A	900 mΩ	1/256
DRV8426	4.5 - 33 V	1.5 A	900 mΩ	1/256
DRV8425	4.5 - 33 V	2 A	550 mΩ	1/256
DRV8886AT	8 - 37 V	2 A	550 mΩ	1/16
DRV8424	4.5 - 33 V	2.5 A	330 mΩ	1/256
DRV8434	4.5 - 48 V	2.5 A	330 mΩ	1/256

The ability to tightly control the ripple current gives smart tune Ripple Control better audio performance than mixed decay schemes. Figure 10 compares the SPL plots of DRV8424 smart tune Ripple Control and mixed decay at 1/256 microstepping. As can be seen, smart tune Ripple Control (green) has up to 10dB lower noise beyond 4kHz than mixed decay (purple). Smart tune Ripple Control only causes an almost inaudible hissing noise, while there is a whining noise when the motor runs with mixed decay.

As is well known, every 3dB reduction in decibel level corresponds to halving of sound energy, and every 10dB reduction corresponds to sound energy decrease by a factor of 10. Therefore, at certain frequencies, smart tune Ripple Control generates only 10% of the noise generated by mixed decay modes.

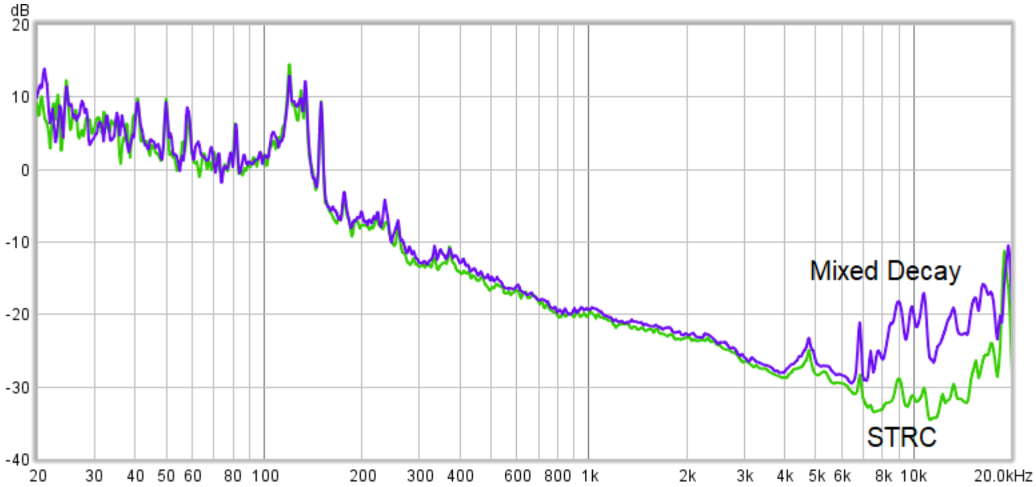

Figure 10. Mixed Decay vs Smart Tune Ripple Control (STRC) at 1/256 Microstepping

The impact of lower ripple current is further illustrated by Figure 11. For the DRV8424, DRV8425 and DRV8426 devices, the ripple current level in smart tune ripple control mode can be adjusted by the TOFF pin. The SPL plot in Figure 11 compares audible noise among the different ripple current settings. 1% and 2% ripple current settings have almost the same ripple current, roughly 50 mA at peak of the sinusoid, due to comparator offset, and so forth. Based on the graph, 1% (green) and 2% (blue) ripple settings show the best audio performance and the 6% ripple (orange) has the worst audio performance over the entire spectrum.

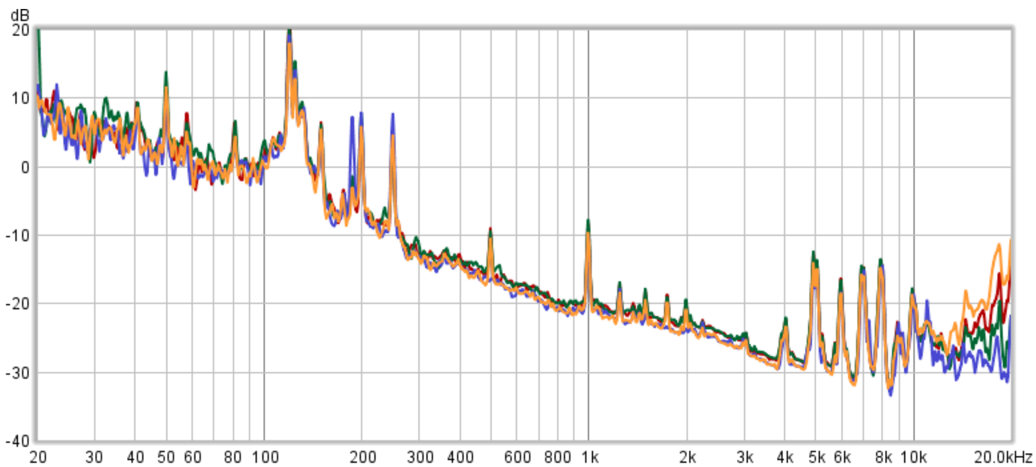

Figure 11. Effects of Changing Current Ripple

3.3.2 Effects of PWM Chopper Frequency

If the PWM frequency falls within the audible band, it manifests itself as a whine coming out of the stepper motor. Even when the motor is stopped and holds the position, the noise associated with PWM frequency will be audible. If the chopping frequency is ultrasonic, a hissing sound can be heard.

Legacy stepper drivers often have a pin which controls the OFF time of the PWM by using two R-C passive components. Designs with 50 µs OFF time are common. When the ON time is added to the OFF time, the resulting PWM frequency will be less than 20 kHz and generate audible noise. Therefore, it can be concluded that noise can be reduced by increasing the PWM frequency. Too high PWM frequency will also lead to higher switching losses, therefore it may not be desirable to increase the frequency well above the audible range. An appropriate PWM frequency value will be between 30 kHz and 50 kHz.

Equation 1 shows the approximate relation between the PWM frequency and the current ripple for the smart tune Ripple Control decay mode. V_M is the supply voltage, V_{BEMF} is the back-emf voltage, L is the inductance of the motor coil and ΔI is the ripple current. As is evident, PWM frequency will be high when the ripple current is low.

$$f_{PWM} = \frac{V_{BEMF} \times \left(V_M - V_{BEMF}\right)}{V_M \times L \times \Delta I} \tag{1}$$

Figure 12 to Figure 15 show the PWM frequencies at different current levels for DRV8424 smart tune Ripple Control and 1/4 microstepping. The PWM frequencies range between 25 kHz and 55 kHz, well beyond the audible range. In general, lowest current ripple results in PWM frequencies that fall beyond 20 kHz and therefore do not impact the audible noise levels from the stepper motor.

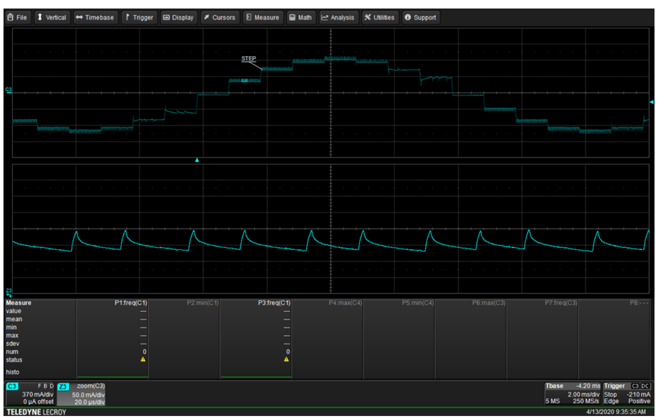

Figure 12. PWM at 38% Level, PWM Frequency is 55 kHz

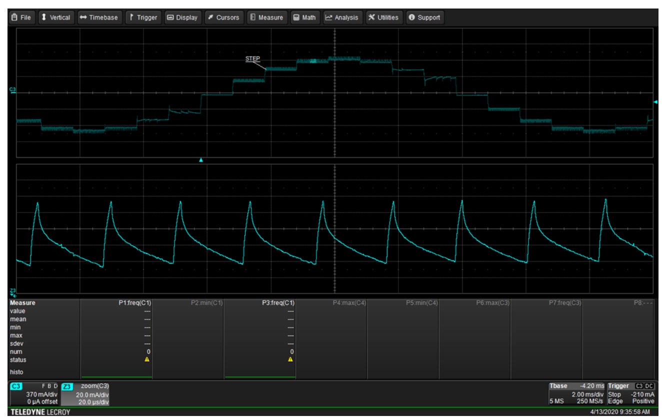

Figure 13. PWM at 92% Level (increasing), PWM Frequency is 44 kHz

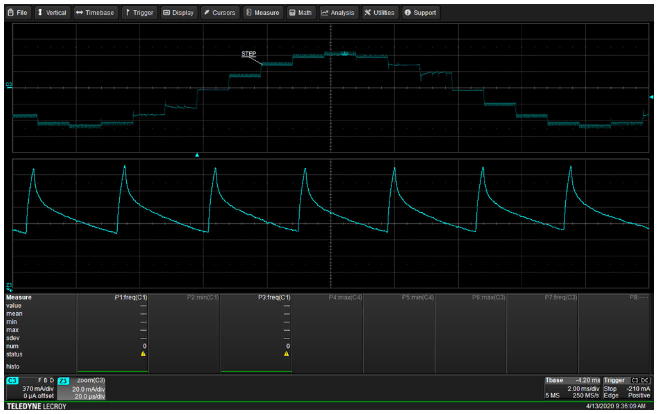

Figure 14. PWM at 100% Level, PWM Frequency is 35 kHz

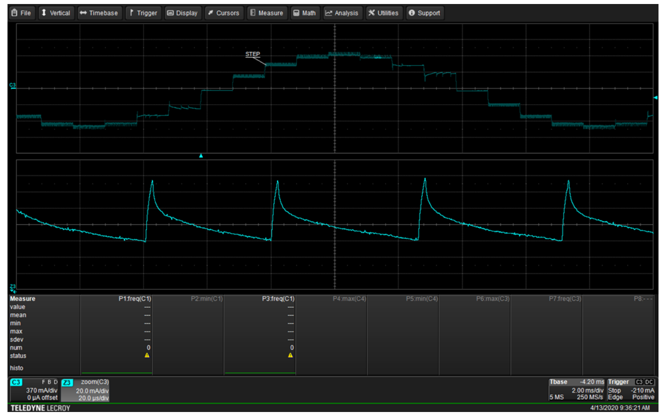

Figure 15. PWM at 92% Level (decreasing), PWM Frequency is 25 kHz

3.3.3 Effects of Current Zero-cross Error

Another potential cause to audible noise can be the smoothness around the zero current crossing. Most legacy stepper motor drivers distort the current waveform around the zero-current crossing when the current changes phase, as shown in Figure 16. The reason behind this distortion is high current-sense blanking time such as 2 µs or higher - which causes the average current for the step to be significantly higher than the intended value. Another reason for distortion around zero-cross is too high OFF time, which causes the average current to be significantly lower than the intended value, as shown in Figure 17. The impact of this distortion is to create unsmooth current waveform - which leads to wobbling, vibrations and audible noise.

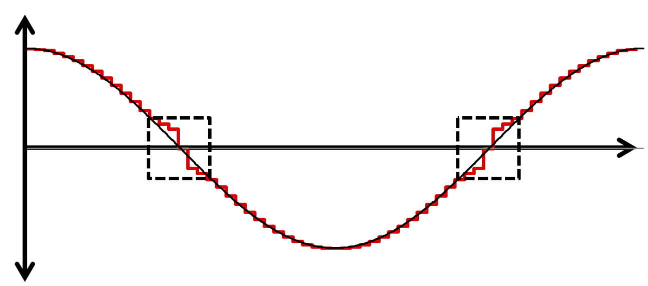

Figure 16. Current Distortion Due to High Blanking Time

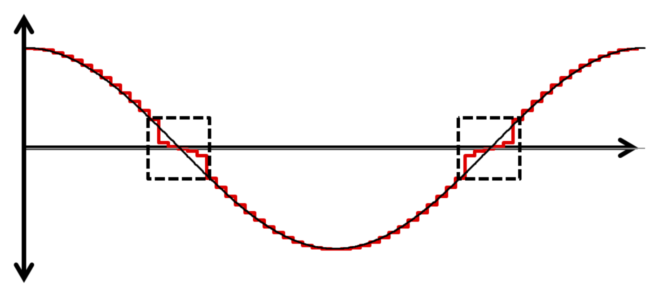

Figure 17. Current Distortion Due to High OFF Time

The blanking time for the drivers listed in Table 1 is only 1 µs, therefore there is no distortion near the zero-crossing region of the coil current. This reduces current and torque ripple and a true sine wave form is approached, resulting in a much smoother motor operation. In Figure 18 and Figure 19, the current zero crossing is shown for DRV8424 at 1/16 and 1/64 microstepping, respectively, showing smoothness around zero-cross.

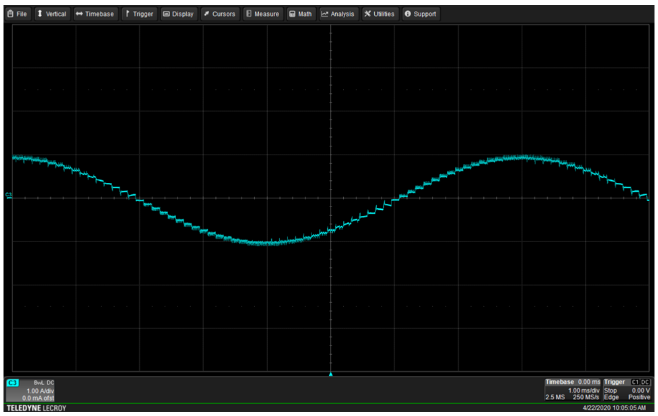

Figure 18. Smoothness of Zero-Cross at 1/16 Microstepping

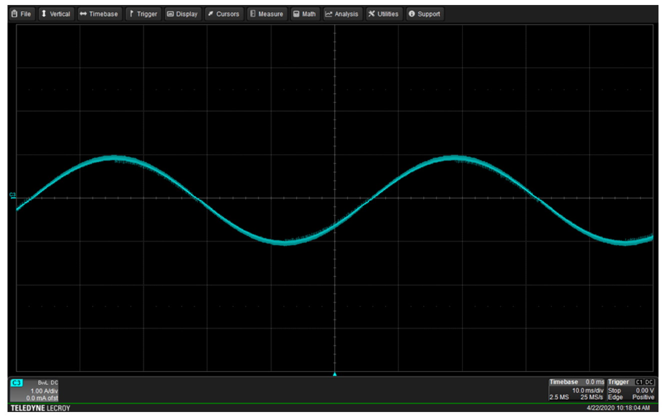

Figure 19. Smoothness of Zero-Cross at 1/64 Microstepping

3.3.4 Effects of Step Resolution and Step Frequency

Low-resolution step modes, like full or half stepping introduce a lot of vibrations that propagate throughout the entire structure of the stepper motor, especially at low speeds. When the driver commands a new step, similar to a pulse response, the rotor overshoots and oscillates around the next position, leading to mechanical vibrations and noise.

To reduce these oscillations, modern stepper drivers employ microstepping to divide one full step into smaller microsteps. This positions the rotor in intermediate positions in between two subsequent full steps. As a result, the rotor is now stepped in much smaller angles, or smaller distances. When switching to a new position, the over- and under-shoots are drastically reduced.

The step frequency appears as a large spike in the SPL plot of a stepper motor. In addition, harmonics of the step frequency continue to occur throughout the spectrum. If the step frequency is between 20Hz and 20 kHz, then the step frequency and all the higher harmonics will appear in the audible range, as shown in Figure 20 for mixed decay with 2 kHz step frequency and 1/4 microstepping.

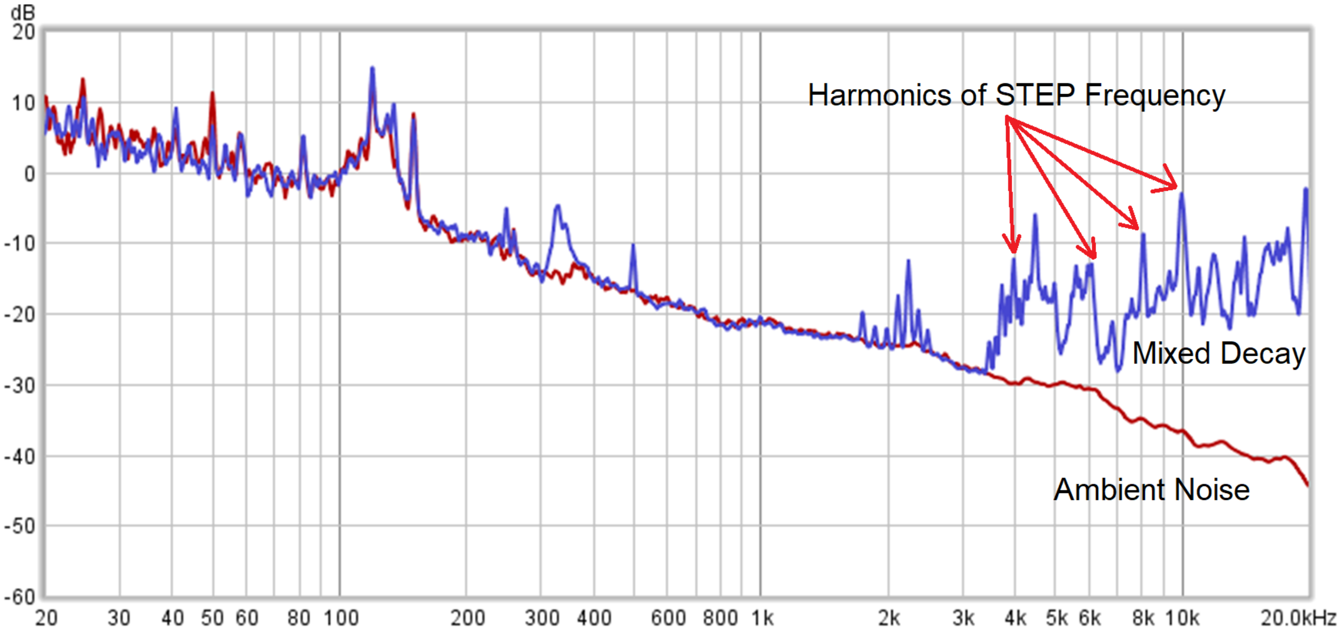

Figure 20. SPL Plot for 1/4 Microstepping, Mixed Decay, Step Frequency = 2000 pps (pulses per second)

One trick to reduce audible noise is by increasing the microstepping level and step frequency together, while maintaining the same motor speed. By selecting a microstepping level which places the step frequency beyond the audio band, quiet motor operation can be achieved. Most of the drivers listed in Table 1 enable this by allowing to increase the microstepping to 1/256, much more than traditional stepper motor drivers.

Figure 21 compares the SPL plots at 1/8 (blue trace), 1/64 (orange trace) and 1/256 (green trace) microstep. The step frequency was 600 pps, 4800 pps and 19200 pps respectively. Microstepping at 1/256 (green) has the best audio performance, and 1/8 (blue) has the worst. At 1/8 steps, there is a clear whining sound. When the microstep is increased to 1/64, the sound softened, but is still audible. When microstep is increased to 1/256 microstep, the sounds vanish and only white noise remains. By increasing the microstep frequency beyond the audible range, the audio nose is reduced and at the same time overall smoother rotation is achieved.

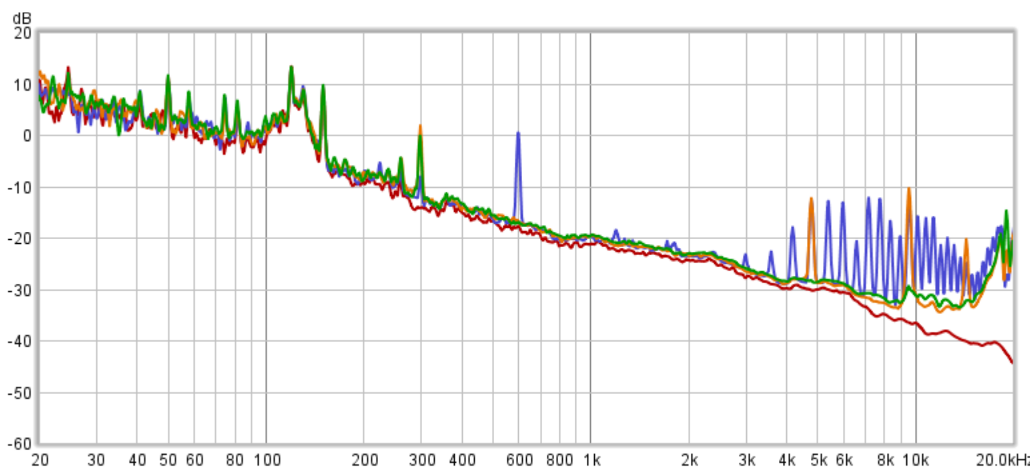

Figure 21. SPL Plots at Various Microstepping Levels

The current waveform at 1/8 microstepping is shown in Figure 22 and at 1/256 microstepping is shown in Figure 23. They show how the current waveform becomes more ideal as microstepping increases.

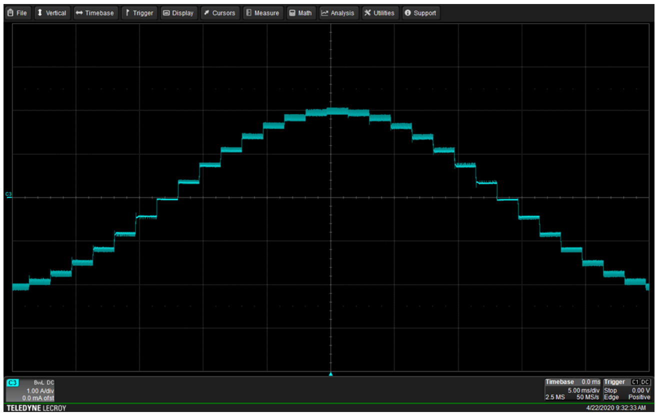

Figure 22. Current Waveform With 1/8 Microstepping, Smart Tune Ripple Control

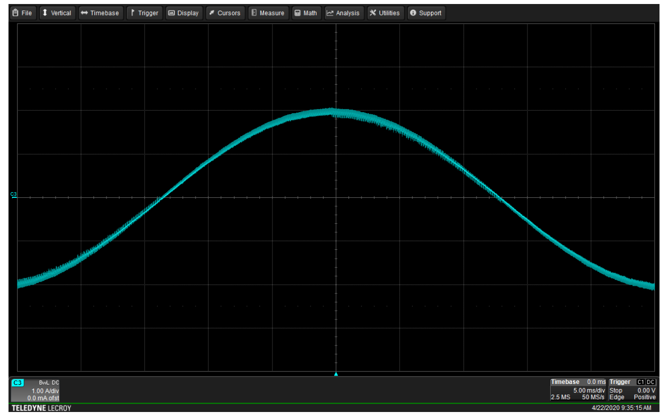

Figure 23. Current Waveform With 1/256 Microstepping, Smart Tune Ripple Control

Typical microcontrollers used in stepper motor applications can easily support step frequencies of 20,000 pps. However, high step frequency also means that the driver needs more microcontroller resources to drive the motor. Therefore, it is not necessary to increase the microstepping to 1/256 for every application. Microstepping level which just about makes the step frequency higher than 15 kHz will result in quiet enough operation for most practical purposes. When the application is expected to work over a wide range of speeds, varying the microstepping level according to the speed helps achieve noiseless operation over the entire range.

One note of caution though - while higher levels of microstepping increases resolution and reduces audible noise, it does not necessarily increase accuracy. This is because microstepping significantly limits the incremental torque of the motor, which means torque of the microstep might not be enough to actually turn the shaft, and in high torque situations the motor may end up skipping some of the microsteps.

3.3.5 Effects of Resonant Frequency

Each stepper motor has a resonant frequency. This is the reason why a stepper motor does not stop immediately when it performs a step, but continues to move slightly forward and backward. The amount of time the motor oscillates is called its settling time. The rate of oscillation matches the resonant frequency. The result is a motor that vibrates and has jitter and noise. If the system damping is low, the resonance can overpower the magnetic field between the stator and the rotor, resulting in lost steps and audible noise.

Once again, microstepping offers an easy and safe way to eliminate resonance, because by increasing the level of microstepping, step frequency can be made higher than the resonant frequency. Dampers are also used to reduce resonances and audible noise. Dampers work by absorbing shock to reduce impulses and dissipating the kinetic energy in resonances. This can eliminate noise, enhance the system transient response and reduce settling time.

4 Summary

Noise from stepper motors can be a big concern and challenge for designers to overcome. But with the right motor driver, electrical audible noise can be significantly reduced by utilizing a number of different features. In addition to pushing the step frequency, motor drivers from Texas Instruments provide automatic decay mode control with smart tune technology, up to 1/256 microstepping, and programmable ripple current magnitude target to ensure smooth motion at frequencies outside of the audible range. The results can be astonishing with reduced level up to 10dB. For more information on TI's stepper motor products, see *TI.com*.

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