Noises in the Night
The factors leading to ultra-quiet electric motors

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Most motor applications produce audible noise, ranging from a slight hum to a mildly offensive whine or even something loud enough to endanger health or require hearing protection. Like many technology issues, the sources as well as the solutions are multidisciplined. Key to finding solutions is an understanding of how the noises arise.

In applications such as medical instrumentation, the acoustic noise level may be a strain on the physician and may unsettle the patient. In industrial applications, higher noise levels may require hearing protection. In other applications, like animatronics or magic show tricks, even a minimal noise may completely upset the illusion.
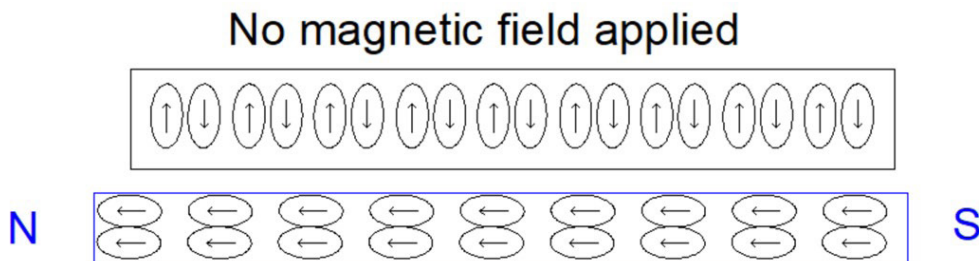
Motor

Let's start with the mechanics of the motor. Although the rotor and stator can often be swapped (so-called inside-out motors), we will keep the discussion focused on the conventional design with an outer fixed stator and an inner moving rotor; the same insights can be applied to different topologies.

Most motors include iron or other magnetic materials (ferromagnetic) in either their rotor or stator or both. Many magnetic materials have magnetostriction properties, meaning that they change their shape or dimensions as a function of the magnitude of the applied magnetic field. The effect arises at the microscopic as the boundaries of and magnetic vector within domains are varied in response to the applied field. The domains try to align with the applied field so as to minimize the free energy of the system. The hum of a common transformer is mostly caused by magnetostriction. The commutation process of a motor involves causing the magnetic fields to vary to cause a torque to be generated between the rotor and the stator, leading to the rotor turning. These changing fields also give rise to changing dimensions, which can cause surfaces of the motor to act as speakers.

In addition to magnetostriction, there is also the simple magnetic attraction between portions of the rotor and stator due to the interaction of their magnetic fields. These forces do not require ferromagnetic materials to be present; the wires themselves will generate forces that result in motion. The coils in many motor designs are dipped in lacquer to help keep them rigid as vibration between wires not only can make noise but also can abrade the insulation. The resulting forces from attraction and repulsion give rise to strains (deflections) in the structures. The design of the

Figure 1 Magnetostriction
Ferromagnetic materials will have their domains align with the magnetic field, causing the physical dimension of the material to expand in the direction of the magnetic field. Some other materials, such as cobalt, contract in the direction of the magnetic field due to different crystal lattice structures.
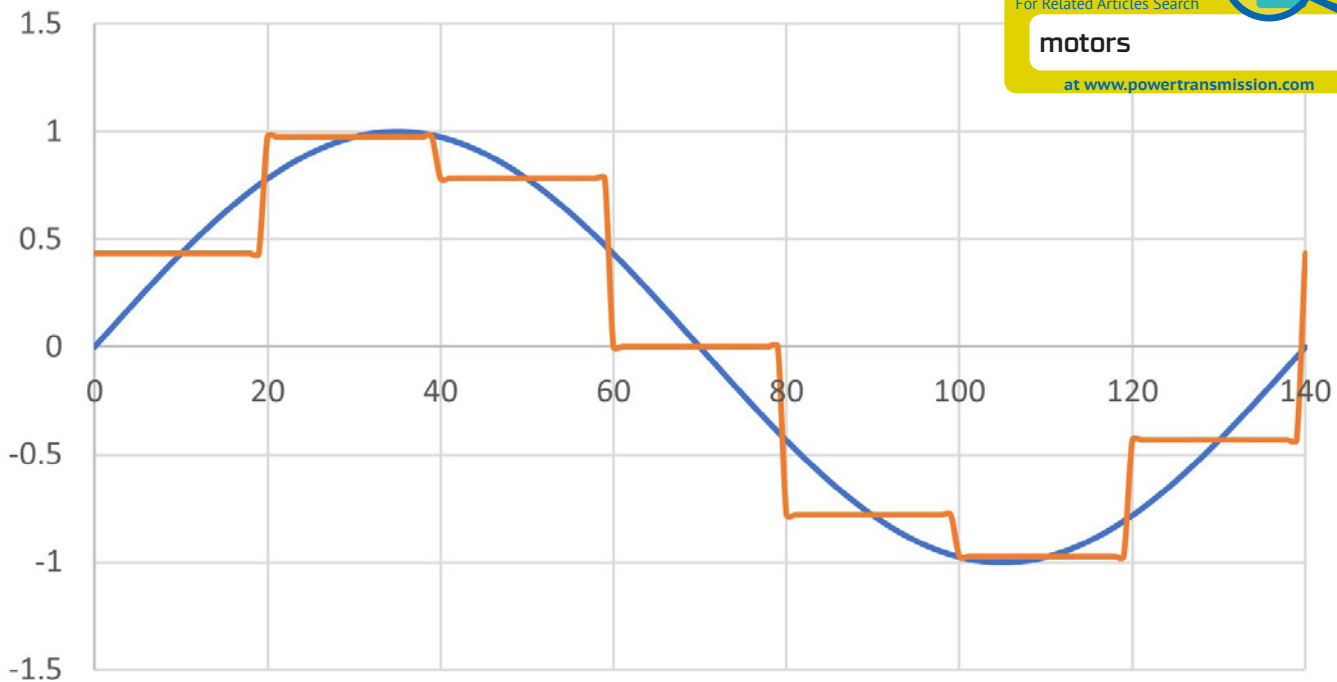
Figure 2 Commutation Smoothness
Driving the current as fast as possible for the next requested current causes an abrupt change in torque resulting in jerk in the system as compared to a smooth change in current.

structure of the different motor types affects the distribution of these forces and the resulting structural deformations. These deformations may also make the motors effectively function as speakers. Note that both magnetic attraction strains and magnetostriction strains will generate acoustical noises according to the way the magnetic field varies, which in-turn follows the winding currents associated with the driving waveforms. The driver and control methodology will be discussed as to how they affect the characteristics of the acoustical noise.

The bearings may also be a source of mechanical noise within the motor. Preloading of the bearing removes the excess play in the bearing, which helps the bearings to have sufficient contact forces to cause the bearings to roll rather than to slide (skidding). Proper preloading also increases the stiffness in the system and extends bearing life. Springs/wave washers are a common method to provide preloading, although solid preloading may also be used, especially in motors with leadscrew shafts built in. Designs that do not adequately preload the bearings often produce significant acoustical noise when the motor is rotating.

The shape of the spaces in the rotor and stator may also give rise to acoustical noise. Hybrid motors typically have sharp teeth on both the rotor and stator and small rotor-stator gaps. Full-step optimized step motors have matching tooth pitch for the rotor and stator (50:50 laminates), whereas microstepping optimized motors have different pitches (typically 48:50 or 52:50 laminates). Some brands of motors will fill in the rotor teeth gaps with epoxy prior to centerless grinding to minimize the noise generated as the rotor teeth pass the stator teeth. A similar effect may be seen with face magnet servomotors versus internal magnet (IPM) designs which have smooth outside diameters on the rotor.

Electronic Drive

The method of commutation and the way in which the drive controls the shape of the current and the rate-of-change of current can have significant effects on the noise levels generated. For servo systems, the control system tuning and damping can further help or hurt the acoustic noise in the system.

The nominal shape of the waveforms driving the motor can substantially affect the acoustical noise. For a 3-phase motor, 6-step commutation with a trapezoidal drive abruptly switches the current forward or reverse for a particular phase, with common drivers only limiting the rate of rise of current by the inductance of the winding and the applied voltage. A 12-step trapezoidal commutation technique adds a zero current step for each phase before reversing the direction of the current. For hybrid motors, the equivalents are full-stepping and half-stepping. The abrupt current changes give rise to acoustical noise both at the fundamental and at many harmonics of the commutation rate. The noise is not only caused by the previously mentioned magnetostriction effects and deformation of the case, but also by the sudden jerk (high rate of change of torque) associated with rapid changes in the winding current torquing the shaft, often with the resulting ringing each time the motor commutates to the next phase combination.

In the hybrid motor realm, there are microstep drives which more closely approximate a sine wave by adding many finer steps to the current waveform to reduce the magnitude of each step change. However, most of the drivers use a current control loop that
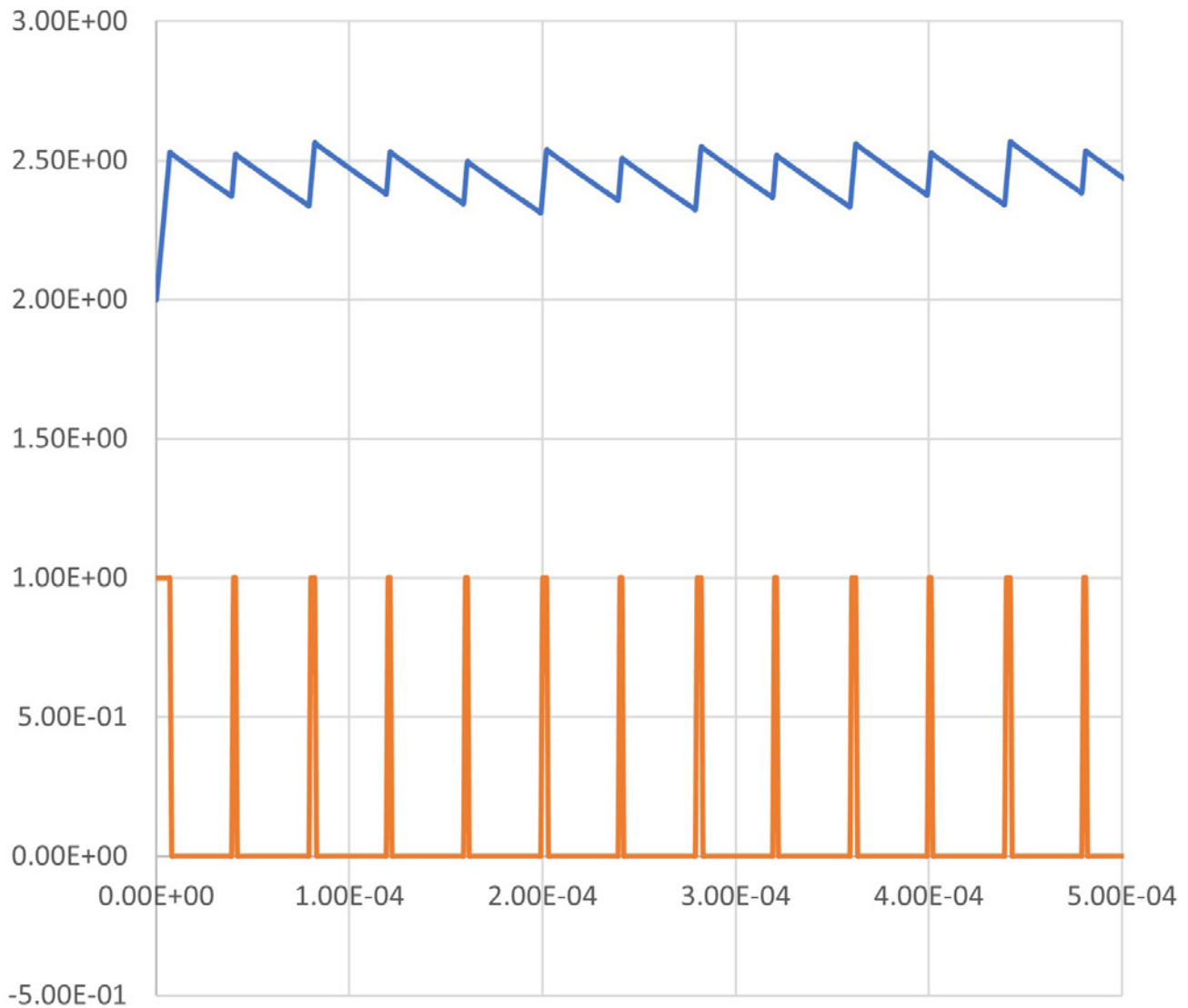
Figure 3   Subharmonic Oscillation
A shorter drive cycle results in more time in the decay portion of the cycle, requiring a longer drive cycle the following PWM cycle. That longer drive cycle results in a shorter decay portion, so the current starts higher and the following PWM cycle requires a shorter drive cycle. This results in a 10 kHz subharmonic which is audible even though the PWM is operating at 20 kHz.

still tries to achieve the next step in the minimum time possible, turning the driver full on until the next desired current plateau is attained. The conventional 3-phase brushless motors are similar with sinusoidal commutation. Note that the design of the motors for trapezoidal 3-phase operation are different than those for sinusoidal commutation, the former having back-EMF waveforms that are typically much squarer than the sinusoidal back-EMF waveforms associated with sinusoidal drive optimized motors. Hybrid motors, similarly, are optimized for either full stepping (50:50 laminates) or for microstepping (48:50 laminates or 50:52 laminates for the common 1.8-degree stepper). When plotting the back-EMF of phase A versus phase B, a full step (50:50

laminate) will plot as almost a square with slightly rounded corners, while a microstep optimized motor will plot as almost a perfect circle.

The noise level generated by a motor may be minimized by minimizing the rate of change of the current in the winding, making it a function of the motor speed, rather than having the current loop attempt to perfectly follow the square change with each new step on the microstep table. This may be done by altering the operation of the current control loop to also utilize a motor speed estimation such that at lower speeds, a lower rate of change is implemented, and saving the rapid changes for higher speeds where motor torque would suffer if the current were not changed at a sufficient rate.

Chopping Drives
Most modern drives use pulse width modulation (PWM) control to vary the currents in the motors. Most current control loops, for both hybrid motors and 3-phase brushless, are responsible for a couple of additional noise generation modes.

The first noise is called "sizzle" and is a caused by amplification of the noise from the measurement of the current being controlled. To minimize heating of the current sensing resistors, very low value resistors are typically used. The resulting voltage from the sensed current passing through the low value resistor is relatively low, so voltage gain must be set fairly high. The noise may be significant compared to the measurement, causing the control loop to

try to react to the perceived current rather than the actual current. The result is the current loop amplifies the measured noise, causing the motor to emit a hissing or sizzling noise.

The second noise related to the chopping drive is a squeal. Although it is common to operate the PWM drive at 20 kHz to 25 kHz, which is typically above human hearing, it is common to hear significant noise in the 6 to 10 kHz range, which is quite audible to humans. The cause of the noise is an instability called subharmonic oscillations. PWM drives for motors are typically operating as a form of buck converter, as the short-term average voltage needed at the winding to maintain a given current is commonly significantly less than the power supply voltage. It is common that these subharmonic oscillations occur at ½ or 1/3 of the chopping frequency, thus a 25 kHz chopper may easily produce significant noise at 12.5 kHz or 8.33 kHz, both of which are quite audible. There are many articles on subharmonic oscillations in buck converts that go into to significant detail, but here is a brief simplified discussion.

The PWM drive drives the winding either at the power supply voltage or shorts the winding or may drive the winding in the reverse direction with the power supply voltage (if the current is already too high). At the beginning of each PWM period, the driver determines if the measured current is higher or lower than commanded current. Assuming the motor is moving slowly or is stationary, the current will have generally decayed due to resistances in the transistors and windings, and the driver will need to turn "on" the drive for a period of time until the current measured again reaches the commanded current. The driver will then short the winding (regeneration mode) until the next PWM cycle begins.

To understand how the subharmonic oscillation sustains, assume this first cycle started with the current somewhat lower than average. The "on" time of the PWM will need to be longer than average to bring the current back up to the commanded level. The current will then decay until the

next PWM cycle begins. Because the "on" time was longer than average, the decay time (recirculate mode) remaining for that PWM period must be shorter if the PWM frequency is constant. The shorter decay time will cause the starting current for the subsequent cycle to be higher than for the last cycle. The PWM on time will be shorter, as it does not take as much time for the measured current to reach the commanded current level before the driver goes again into recirculate mode. This means that more time will be spent in the recirculate mode for this cycle, resulting in a lower measured current at the start of the subsequent cycle. This long cycle, short cycle as described would be a second subharmonic, or would happen at half of the chopping frequency. By a similar process, you can also commonly cause a third subharmonic oscillation. The resulting periodic current variation causes an audible squeal (or "singing") which can be very irritating when exposed to it for a full work shift. The high frequency of this current variation generally makes motor a more effective speaker whereas very low frequency variations generate little noise.

A Smarter Current Loop
The rapid change in current at commutation, sizzle, and subharmonic oscillation may all be overcome by using a current estimator modeling the motor rather than directly measuring the motor current. The voltage applied to the motor, the motor inductance, the motor resistance, the motor back-EMF, and the motor speed and position may be used to estimate the current. The resulting current loop does not have sizzle, and does not have the subharmonic oscillation squeal, and may be further configured to limit the rate of change of current to only that required for the instantaneous motor speed.

Control Method
The motor noise may also be significantly affected by how the motor is controlled. An open loop step motor is typically driven at full current regardless of the load. The torque takes a

step at each step or microstep change, resulting in a significant jerk at each transition. Both low speed resonances and mid speed resonances may create extra motion oscillations, resulting in significant acoustical noise. The magnetostriction and attraction forces are also maximized by using full current, again contributing to noisy operation. Servo control uses only the current needed to generate the desired motion. This minimizes both the current and the rate of change of the current. Electronic damping can further reduce the vibration of the load when rotating. When combined with a smart current loop, the motor acoustical noise can be greatly reduced.

Summary
The resulting motion, of both hybrid servomotors and 3-phase AC brushless servomotors—both using sinusoidal commutation—can be essentially silent operation up to a few hundred RPM. When testing one Quick-Silver NEMA 17 frame hybrid servomotor, we used a sound meter that was designed to be used at a 5-foot distance for its calibrated measurement at only 3 inches (20x closer) in an attempt to get any sound to even register. As the sound energy halves for each doubling of distance (square law), so sensitivity doubles (~ 6 dB) for each halving of distance. We saw a meter reading of less than 50 db with the meter 20x closer than calibration distance, indicating the noise contributed by the motor was likely less than 24 dbA, virtually silent operating at a few hundred RPM.

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