ThinGap®
2064 Eastman Avenue #107 • Ventura, CA 93003
805.477.9741 • fax 805.477.7535

Motor Eliminates Cogging Torque for Ultra Smooth Servo Track Writer

By David Rich
Chief Engineer
Surface Engineering

Air bearing spindles for such demanding and close-tolerance applications as wafer manufacturing and handling equipment and servo writers require especially smooth velocity. Typically, we use an 8-pole slotted brushless DC (BLDC) motor in these applications. However, for a recent servo writer application the spindle nose deviation error of 0.15-micro-inch (3.81 nanometers) was unacceptably high. While looking for a solution, we discovered a new slotless BLDC motor technology without wire windings developed by ThinGap, Inc., which minimizes cogging torque and torque ripple to deliver extremely smooth velocity.

Most engineers do not realize as the nose of an air-bearing spindle revolves it creates a measurable asynchronous motion error. Although 0.15-micro-inch is quite small, our customer not only measured it but found it unacceptable for their specific application. Generally, errors are either synchronous or asynchronous. Synchronous motion errors occur once every revolution, allowing them to be stripped out. Asynchronous motion error is irregular and therefore more difficult to address.

In this case, the BLDC motor's 8-poles were visible in the error motion of the spindle nose pointing to cogging as the error source. Essentially, we found that cogging torque of a slotted BLDC motor influences the shaft to some degree, which in turn influences the encoder, its output and feedback as well as error motion at the spindle nose.

Slotted BLDC Motors

In conventional slotted BLDC motors, the stator features slotted steel laminations that form a uniform stack with a series of teeth. Inserted into each of the slots is a wound copper coil that produces the electromagnetic field. Together, the laminated stack and wound copper coils form the stator assembly. The return path completing the magnetic circuit consists of the laminated material outboard of the copper windings in the stator and the motor housing.

Cogging results when the permanent magnets on the rotor seek preferred alignment with the teeth on the stator. Winding copper wires through the slots tends to increase this effect. As magnets pass by the teeth, they have a greater attraction to the iron at the ends of the teeth than to the air gaps between them. This uneven magnetic pull causes the cogging, which prevents smooth motion; and ultimately leads to torque ripple, efficiency loss, vibration and noise. This uneven magnetic pull also causes a radial deflection as each magnet "locates a lamination tooth, that is: the magnetic radial pull is not balanced.

Slotless BLDC Motors

A slotless BLDC motor overcomes many weaknesses of iron core motors by using ironless core coils made with magnet wire. Instead of winding copper wires through slots in a laminated iron stack, as is the case with slotted BLDC motors, washer shaped silicon-steel laminations support the exterior of the wire windings. The laminations provide the return iron for the magnetic structure but eliminate the teeth. Thermoplastic encapsulates the windings to maintain orientation with the stator laminations and housing assembly.

This configuration eliminates stator teeth and minimizes cogging. The stationary laminations have eddy current losses, or drag on the spindle reducing efficiency and creating more heat. However, only 50% of the space the winding occupies is copper, resulting in a large magnetic gap, reducing magnetic flux density. The air gap between the stator and rotor is very wide, further reducing magnetic flux density.

The copper packing density of circular wire, larger air gaps, wire winding structure and higher electrical resistance limit performance. The traditional slotless brushless motor uses conventional copper wire windings and silicon-steel laminations, eliminating cogging, but the magnets sweeping the laminations cause lamination losses.

This creates velocity and torque ripple. Velocity ripple is the variation or oscillation of speed over time and torque ripple is the variation or oscillation of torque over time.

In some applications, encoders with high data count feed back can measure velocity over time and correct the drive current to compensate for velocity ripple however high speed applications cannot benefit from these encoders due to their speed limitation. When motor cogging is the source of velocity ripple, corrections made by the drive can actually be detrimental since the corrections are based on encoder data that has error due to cogging. In some cases this can excite vibrations which increase the errors.

ThinGap Motors

The ThinGap BLDC motor replaces the wire windings used by conventional iron and ironless core BLDC motors with a freestanding coil that is a composite structure made of a precision-machined copper sheet, glass fiber and polyimide. This configuration allows significantly higher copper packing density than either round magnet wire or even square magnet wire.

Most conventional BLDC motors (slot and slotless) rely on a rotating magnetic field that introduces varying degrees of cogging. This results in hysteresis losses, which is the primary cause of cogging. In other words, as the magnets pass the magnetic detent, no matter how minute, it causes the shaft to seek that position.

ThinGap BLDC motors eliminate relative motion between the rotor and housing return path by using a fixed magnetic field with a rotating return path, resulting in hysteresis losses so small it requires ultra precision instrumentation to measure. This virtually eliminates cogging, which minimizes velocity ripple and torque ripple. As a result, our air-bearing spindle provides very smooth velocity and torque.

The inductance is extremely low, which has made it a little difficult to drive because it does not use a standard off-the-shelf amplifier. The amplifier has to address exceedingly low inductance motors. We tried using an inductor between the amplifier and the motor, but that introduced a propagation delay in the circuit.

Any deviation of the back EMF voltage or current waveforms from a perfect sinusoidal signal causes torque ripple in conventional BLDC motors. Therefore, the ThinGap motor provides a sinusoidal current waveform to minimize torque ripple. -Matching the motor with a sinusoidal drive amplifier produces the proper coupling of waveforms that results in extremely low torque ripple.

ThinGap motors have an inherently low harmonic distortion of the back EMF waveform due to their unique construction and configuration. When the motor receives a smooth sine wave in, it provides very smooth operation. A conventional BLDC that receives a smooth sine wave in, does not guaranty smooth operation. For example, our application uses a NEMA 23 BLDC motor part set with a torque ripple less than +/- 0.045%.

Because the construction of a ThinGap motor is so different from conventional BLDC motors, we were able to take advantage of its mechanical design and design our air bearing around it. Additionally, the back end of the motor is unique and we redesigned the back end of the spindle accordingly.

ThinGap®

2064 Eastman Avenue #107
Ventura, CA 93003
tel: 805.477.9741
fax: 805.477.7535