MOTORIZATION OF PRECISION BEARINGS AND SPINDLES

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OVERVIEW

The ideal motor for precision machines is one that produces a controlled force in a single direction with negligible heat generation. Practical motors generate off-axis forces that interact with the finite stiffness of bearings and servo systems to generate error motions. Error motions in the direction of travel lead to a velocity ripple, and errors orthogonal to them are the geometric error motions. In spindles these are radial, axial, and tilt error. In linear slides, these can be straightness, pitch, roll, and yaw. Current-carrying wires that generate force also generate heat, and this heat will lead to thermal deformations and loss of accuracy if not properly handled in a system.

The purpose of this paper is to present a tutorial of commonly available motorization options for precision motion control systems. It begins with a review of motor fundamentals, shows examples of the motors being applied in practice, and provides suggestions for reducing the unwanted influences of parasitic forces on the axis motion. In general, the design of linear and rotary systems is identical. Specific differences will be noted where they appear.

MOTOR FUNDAMENTALS

Drive motors used in precision bearings and spindles are predominantly of a *brushless DC* design. Linear, rotary, and curved (arc-segment) motors all have strong similarities in their design, and will be discussed interchangeably. They produce force through the Lorentz force law, $\mathbf{F} = \mathbf{J} \times \mathbf{B}$, where $\mathbf{F}$ is the force density, $\mathbf{J}$ is the current density, and $\mathbf{B}$ is the magnetic flux density. Typically the magnetic flux and current paths are designed to be orthogonal to each other, and so the force on a wire of length l carrying a current i in a magnetic field is $F = ilB$. The force is linearly proportional to the applied current. Different styles of brushless DC motors vary mainly in their approach to creating physical realizations of the Lorentz force law.

Motor Construction

Three basic styles of brushless DC motors are available: slotted, slotless iron core, and ironless. Slotted motors are the most efficient, dissipate the most heat, and produce the worst parasitic forces. Ironless motors are the least efficient and can be difficult to cool, but generate the smoothest force. Slotless iron core motors are between the two extremes, having no exposed teeth, but iron laminations behind the windings. All of the motors described here are of a frameless design, having a coil assembly and a magnet assembly. They are not stand-alone but instead installed as an integral part of a precision direct-drive motion control axis.

Slotted Motor Designs

Slotted motor designs are named for the laminated iron "teeth" in which the coils are embedded. The teeth of these laminations extend to the surface of the coil assembly, and serve to strengthen and focus the magnetic field created by the current flowing through the coils. The laminations are typically made from some type of a Nickel-Iron alloy specifically designed for use in motor applications. The iron is laminated (made from thin sheets) rather than made from a solid to reduce the influence of eddy currents. Eddy currents are current loops that form within the iron due to the applied magnetic field. They produce heat, but do no useful work and are a major limitation in high-speed operation. Thin laminations separated by insulating layers reduce the size and effect of eddy currents. Slotted motors are typically single-sided with teeth either on the face of a flat coil (in the case of a linear motor) or on the inner annulus of a stator (for rotary motors). The coil interacts with a single-sided magnet array that is either on a flat plate or around the outside of a motor shaft. Figure 1 shows a schematic of a typical linear slotted motor design.

Slotted motors have a very prominent cogging force due to the propensity of the iron laminations to align to the magnetic field of the permanent magnets. This can be felt as detent locations when the axis is moved by hand. Typical designs have either the permanent magnet assembly or coil laminations skewed (set at an angle) to reduce this effect. However, the efficiency of the motor is reduced by the sine of this skew angle. The cogging force enters the control loop as a position-based disturbance. When moving at a constant velocity, this appears as a single-frequency disturbance, and is usually a prominent peak in an FFT of the position or velocity error. At typical linear motor speeds and motor sizes, this sinusoidal disturbance will be below 100 Hz, and so can be somewhat attenuated by the closed-loop servo control. In rotary motors, the surface velocities tend to be much higher and cogging disturbances can be a few hundred to a few thousand cycles per second. This is typically beyond the bandwidth of the closed-loop servo system, and so is not significantly attenuated by typical PID loops.

Slotted motors have a strong attractive force between the laminations in the motor coil assembly, and the exposed magnets on the magnet track. As an example, a typical iron core linear motor (the Aerotech BLMFS5-142) has a coil assembly with a face area of 50 mm x 142 mm. It has a continuous force rating of 175 N, but also generates over 2400 N of attractive force between the coil and track at a nominal 0.75 mm gap. The bearings on the linear axis must be designed to carry this additional load, which can be significantly higher than the nominal payload on the axis. This attractive force can also be put to use as the preload for a bearing system, as demonstrated by Slocum with a low-cost air bearing system [1].

Assembly and maintenance procedures are needed for safe installation of slotted motors. Aerotech typically installs open face linear motors by bolting the coil assembly to the carriage before any magnet tracks are installed. We then install the track in several small sections, keeping the carriage pushed far away from the track area. After installing the first tracks, the carriage is pushed over these ("capturing" the field of the track with the coil) and the remaining tracks are installed. Warning labels and tamper-resistant screws should always be used.

Slotted rotary motors have an attractive force as well, but in a centered system this is nominally balanced (aside from manufacturing tolerances). Bearing load is normally not a problem, but safe installation procedures must still be adhered to. The slotted coil assembly has a tendency to rapidly snap the magnetic rotor into place axially, and so the two pieces should be held in a fixture that allows for a controlled assembly. In some cases, the slotted rotary motor can be given a deliberate radial force with an asymmetry in the lamination design (milling away material for instance). This can be used to introduce a preload into the bearings if appropriate.

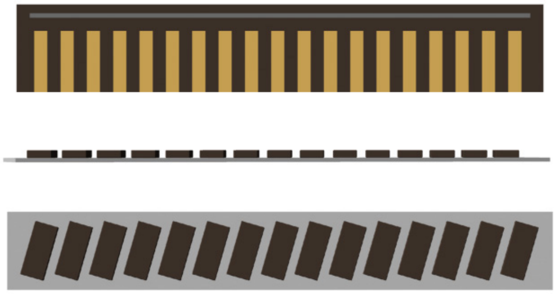

FIGURE 1. Construction of a typical slotted linear motor showing coils between teeth of a laminated iron core and a single-sided magnet track. Magnets are often skewed to reduce the cogging effect.

Slotless Iron core Motor Designs

A variation on the slotted motor design retains the iron backing to the coils, but eliminates the "teeth" in the laminations that protrude through to the coil surface. This extra distance between the iron laminations and magnets significantly reduces the cogging effect. In linear motor designs, the cogging occurs at the front and rear edges of the coil assembly. In rotary motors, the laminations are continuous, and so there is usually no edge to produce cogging. In many applications, the magnetic disturbances are low enough to call this a cog-free design. However, in precision applications, the magnets still interact with the iron in the core enough to generate a disturbance force. Conceptually, the magnets in the rotor slightly magnetize the iron in the lamination, creating a preferred location. This can be felt as a restoring force when an air-bearing spindle motorized with a slotless iron core motor is moved slightly. In higher-speed applications, this cogging force affects both servo tracking errors and geometric error motions of the axis. Hale [2] details the influence of these forces on a precision air-bearing spindle. The attractive forces between a slotless iron core motor coil and the magnet assembly are lower than for a slotted design, but still very significant and potentially dangerous. Appropriate assembly and service cautions are still required.

Ironless Motor Designs

Ironless motors, exactly as their name implies, contain no iron or otherwise magnetic elements in the coil assembly. The linear versions are commonly known as "U-Channel" motors, and are manufactured by a number of vendors in comparable sizes. Figure 2 shows a photo of typical U-Channel ironless linear motors. Because there is no iron in the coil assembly, there is no cogging force generated. Assembly is also much easier since there is no attractive force between the coil and magnets. With an effective commutation scheme, the applied force is independent of position. This results in very smooth motion that is appropriate for scanning and contouring applications.

FIGURE 2. This photo shows of a typical family of U-channel (ironless) linear motors. The largest size has a cross section of approximately 50 mm x 150 mm. The magnetic field is largely confined to the track, and the tracks are stacked as needed for the required travel.

Ironless motor designs are inferior to other iron core designs in their force density (due to the lack of iron for increasing the magnetic field strength) and the conduction path for removing heat from the coil. Figure 3 shows a cutaway of a typical U-channel linear motor design. The epoxy matrix used to bond and protect the coils does not provide as good of a conduction path as does the iron in other designs. Convective heat transfer between the coil and magnet track is significant. Water cooling techniques can be applied in temperature-sensitive applications to reduce expansion-induced accuracy losses. Cooling plates should be used to transfer heat from both the coil and track independently.

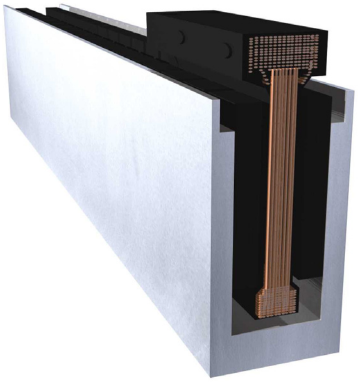

FIGURE 3. This cutaway of a U-channel linear motor shows the coil assembly inside of a magnet track. The coils are potted in an epoxy matrix for durability and electrical isolation.

Ironless rotary motors are less common, but are available from several manufacturers. Torque density and peak currents are both reduced from comparable iron-core designs. El-Husseini and colleagues present a thorough analysis of an ironless motor used for precision motion control applications [3] [4] [5]. This motor is a standard slotless iron core design (Aerotech S-50-52) in which the laminations have been replaced with epoxy. Parasitic forces are very low, resulting in the smooth motion needed for this application. However, both the torque constant and current rating of this motor are roughly half that of the standard iron core design.

Ironless designs, and U-channel motors in particular, are the appropriate choice in applications where stray magnetic fields are not permissible. The opposed-magnet arrangement of the U-channel tracks largely captures the field. However, for highly sensitive applications, low fringing motors can be used that include extra shielding to further contain the magnetic field. Figure 4 shows the magnetic field around a standard magnet track, with peaks occurring at the ends. Figure 5 shows the measured magnetic field strength over a work zone in a particular shielded implementation. In this case, peak-to-peak magnetic field variation was approximately 25 mGauss over a 300 mm diameter area.

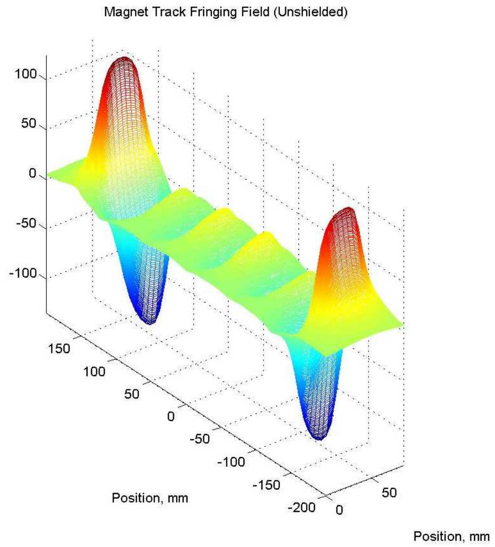

FIGURE 4. The fringing field of a U-channel magnet track is highest at the ends. Units of field strength (vertical axis) are in Gauss. Shielding techniques can further captivate the stray fields.

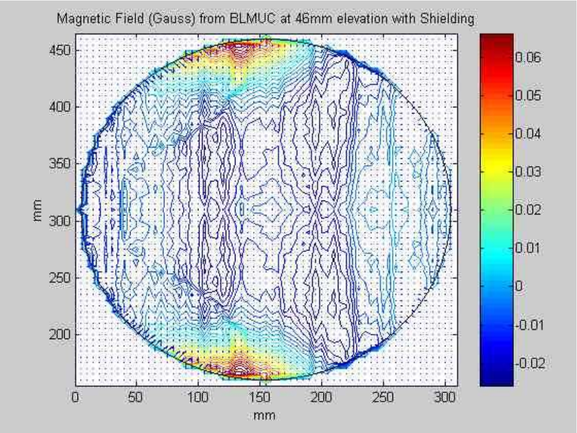

FIGURE 5. In this example, shielding techniques have been applied to reduce the presence of stray magnetic fields to 25 mGauss variation over a 300 mm diameter work zone.

Drive Electronics

Drive electronics send the appropriate current to each phase of the motor. In the past, these were essentially analog amplifiers for converting a controller output into a higher-power signal. As such, they contained an analog current loop with compensator gains set by resistors and capacitors. These were tuned for average performance over some range of motor characteristics (resistance and inductance).

Analog drive electronics have largely been replaced by microprocessor-controlled digital control loops. Current loop gains can be tuned more easily and with finer resolution and repeatability than was possible with analog electronics. It is also much easier to maintain uniform scale factors and offsets among the three phases of power electronics, and sinusoidal commutation can be offloaded from the main processor to the drives.

There are several algorithmic methods available for generating smoother force from all of the different motor designs. Force mapping is particularly appropriate to slotted motors (linear and rotary) and slotless iron core linear motors. The user scans the axis at low speed, generating a bi-directional map of the current that is required to overcome the cogging force. This map is used to feed forward the required current to offset the cogging force at each axis location. It is a simple and robust method that is usually taken as a first step.

Another feedforward-type scheme applied to precision motors is non-sinusoidal commutation. Most commutation schemes are established assuming the interaction of perfectly sinusoidal magnetic fields and current densities. Practical manufacturing techniques make this perfection impossible, and non-sinusoidal commutation technique add higher-harmonics to the dominant frequencies. To apply this technique, measure the back EMF of the motor in question, and calculate the Fourier series coefficients. It is often the case that averaging among multiple magnets and phases in a design produce a back EMF that is far more sinusoidal than would be expected. However, any additional harmonics can be added to the commutation table in place of simple sinusoids.

The cogging force seen in any iron-core motor can also be reduced with a supplemental feedback algorithm. Adaptive feedforward cancellation, also known as repetitive control, is appropriate for attenuating disturbances that occur at well-known frequencies (spatial or temporal). Conceptually, the controller applies increased servo stiffness at discrete frequencies

[6]. When tuned correctly, the controller can eliminate tracking errors at these discrete frequencies. Because it is a feedback technique though (rather than feedforward) improper tuning can lead to instability. This technique is best applied in constant-velocity applications such as spindles or scanning stages.

CONCLUSIONS

In this paper, we reviewed three common styles of motors used with precisions spindles and bearings. Slotted motors have the highest force density and best thermal conductivity, but also generate high attractive and cogging forces that must be allowed for in the design. They are most appropriate for point-to-point position applications where velocity regulation during the move is not critical. Slotless motors still have an iron core. The cogging force is greatly reduced, particularly in rotary motors. This design usually represents a good compromise between torque density and cogging for many rotary applications. Linear iron core slotless motors still possess a cogging force whenever the iron backing to the motor passes over a magnet pole. They are again most suitable for point-to-point applications, but can be used in some contouring applications if control algorithms are used to attenuate the influence of the cogging force. Ironless motors are most commonly used in linear applications. They are available as a "U-channel" design from a number of manufacturers in a wide range of sizes. There is no magnetic attraction between the coil and magnet assembly making installation and servo control straightforward. These motors are very appropriate to scanning applications where contour errors are critical. The downside is lower current ratings that comparably sized iron core motors due to the relatively high-resistance path for heat removal from the coils. Completely ironless rotary motor designs are less common, but available for precision spindle applications. In all cases, correct pairing to the drive electronics is critical to optimal operation. Microprocessor-controlled amplifiers can employ commutation schemes and algorithms that reduce the effect of cogging forces. They also have current loops that are balanced and tuned to the specific motor and application characteristics.

REFERENCES

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