The Straight Attraction PART ONE

Direct-drive linear motors are gaining popularity with motion control system designers and are rapidly replacing traditional rotary-to-linear-motion conversion technologies such as motor/lead screw and belt-drive systems. Linear motors provide distinct advantages over these established techniques: higher speed and acceleration, greater accuracy, and elimination of backlash. DC permanent magnet motors comprise almost exclusively the new generation of linear motors, with the great majority incorporating neodymium-iron-boron (NdFeB) permanent magnets.

Tony Morcos
The Magnequench Technology Center

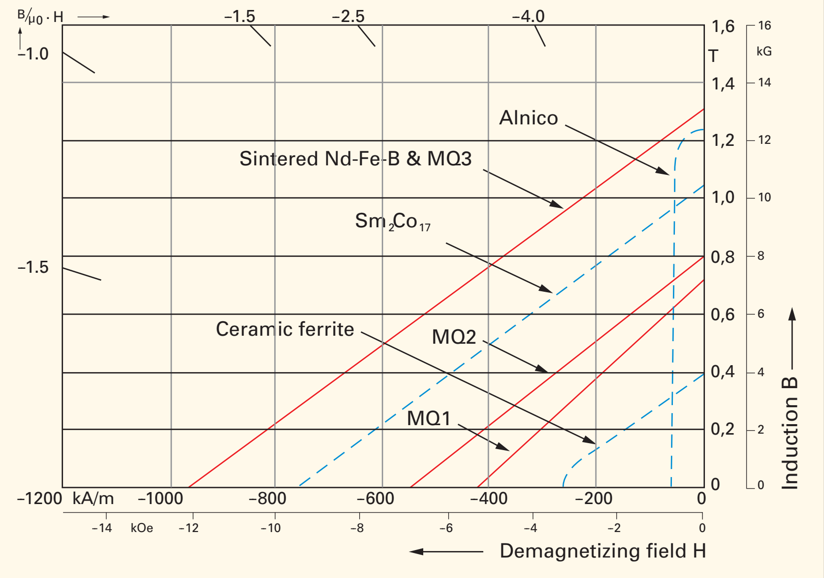
Unfortunately for designers, available magnet shapes usually dictate the magnetic circuit designs for linear motors—not vice versa. We'll look at how the many available grades and geometries of NdFeB magnets are most effectively applied to a variety of linear motor designs. I'll also give an overview of the metallurgy and fabrication of NdFeB magnets to explain which magnets are best suited to specific linear motor geometries.

Metallurgical Overview

A variety of permanent magnet materials are available commercially. Figure 1 shows the flux density (B) vs. magnetizing force (H) demagnetization curves (hysteresis loops) for the most common: AlNiCo, ceramic ferrite (generally $BaFe_2O_3$ or $SrFe_2O_3$), samarium cobalt (often $SmCo_5$ or Sm_2Co_{17}), and various grades of NdFeB. The latter, introduced in 1985, provide the highest energy of all permanent magnets, and this material has enabled the transformation of linear permanent magnet motors from a laboratory curiosity into a viable commercial product. Their high energy product (BH_{max}) and stiff intrinsic coercivity (H_{ci}) allow high magnetic flux densities to be pushed across the large air gaps inherent in most linear motor designs, while withstanding the demagnetizing fields generated by these linear motors' coil windings.

The primary composition of our featured magnets is $Nd_2Fe_{14}B$, though other trace elements and compounds are added, usually to improve the material's magnetic characteristics with respect to temperature, to increase its intrinsic coercivity, or both. Every NdFeB magnet begins its life in powder form and is then pressed into a magnet. There are different methods of making and pressing this powder that yield quite different material characteristics, and they provide unique and distinct magnet properties.

Direct-drive linear motors are benefiting from the use of NdFeB permanent magnets.



1 Typical room-temperature demagnetization curves for common commercially available permanent magnet materials.

One common method of making an NdFeB magnet is via standard powder metallurgy processing, pressing, and sintering. The alloy is cast into ingots, which are coarsely ground in a jaw crusher and then jet milled into a fine powder (3–5 micron particle sizes). This powder is then pressed under the presence of an aligning magnetic field, which orients the anisotropic domains. The "green" pressed magnet form is then sintered under a vacuum and annealed to give it structural integrity. The resultant product, which still isn't magnetized, is then machined to final shape, usually via grinding with a diamond wheel, and then coated to prevent oxidation. The final step in the process is to pulse magnetize the magnet, either as an individual part or *in situ* within the motor assembly.

Another NdFeB processing method is via the jet casting/rapid solidification of the molten alloy (i.e., melt-spun NdFeB). In jet casting, the ingots are melted and ejected onto a chilled, rotating wheel. The molten alloy rapidly quenches into ribbons of NdFeB. These ribbons are ground into particles roughly two orders of magnitude larger than those in the sintering process, with each particle consequently containing hundreds of isotropic magnetic domains. These particles are chemically stable, unlike the fine anisotropic powder used for sintered NdFeB magnets. Melt-spun powder can then be processed in three different fashions to make a finished magnet.

The first processing path combines the isotropic powder, which is first annealed, with any of a variety of thermoplastics for injection or compression molding into a "bonded" magnet, also referred to as "MQ1." Bonded magnets can be produced in a variety of shapes, which are still isotropic, allowing subsequent magnetization along any axis. As-pressed dimensional tolerances meet most application requirements so that subsequent grinding isn't necessary. The pressed magnet can then be coated, though magnets made from melt-spun ribbon aren't nearly as susceptible to oxidation as sintered NdFeB magnets. Finally, the magnet must be magnetized.

A second way to make NdFeB magnets from melt-spun isotropic powder is to hot press it, forming a fully dense isotropic magnet called "MQ2." Like MQ1, MQ2 magnets can be produced in a variety of shapes, as-pressed dimensional tolerances are tight enough so that subsequent grinding isn't usually necessary, coating is optional (but recommended), and, of course, magnetization is required.

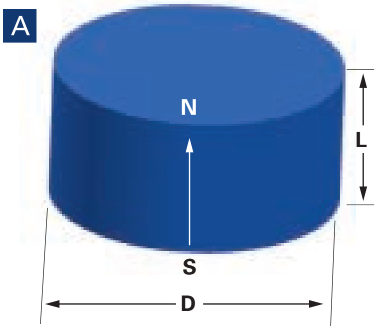
The third path is to subject an MQ2 magnet to hot plastic deformation, which aligns its crystalline structure in the pressing direction, thereby imparting magnetic alignment (anisotropy) to the magnet. Because this anisotropy is mechanically applied, no aligning magnetic field is required during pressing. Such fully dense, anisotropic magnets fabricated from melt-spun isotropic powder are called "MQ3," and their energy product is roughly equivalent to that of sintered NdFeB magnets. Like MQ1 and MQ2, the as-pressed dimensional tolerances for MQ3 magnets can be made tight enough so that subsequent grinding isn't necessary. Coating is optional (but recommended) and magnetization is required.

Magnet Orientation and Geometry

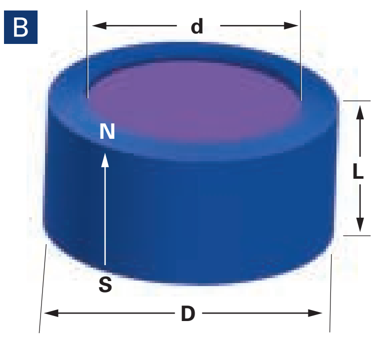
Anisotropy is imparted to a magnet so that its magnetic properties are enhanced in a preferred direction. For example, in a ring magnet, the anisotropy can be either radial or axial/transverse. The highest energy permanent magnets, sintered NdFeB and MQ3, must therefore be anisotropic, but this limits the geometries and magnetic orientations available to linear motor designers. Isotropic NdFeB magnets, e.g., MQ1 and MQ2, have lower energies than their anisotropic counterparts, but they provide greater flexibility to the designer when creating the motor's magnetic circuit.

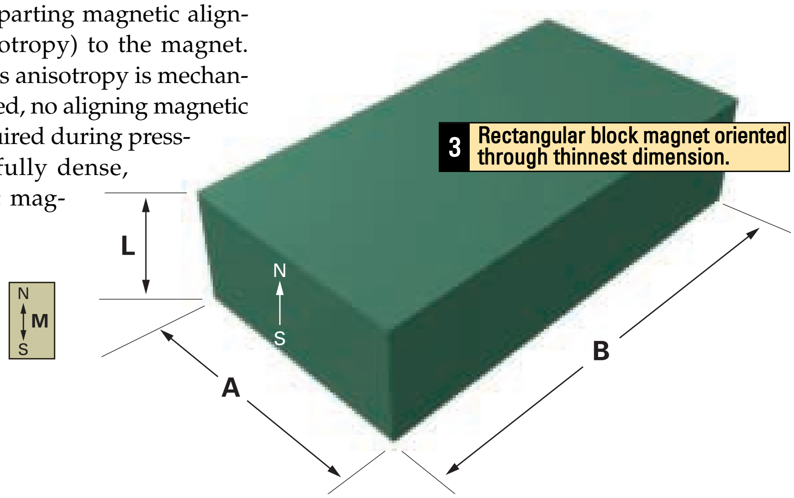
The simplest anisotropic NdFeB magnet to manufacture is a right cylinder (disk) with axial orientation. Figure 2 shows this magnet geometry as well as a useful variation of this shape—a disk with a hole (donut). The hole can be employed for mechanical assembly features, cooling or optical plumbing, feedback sensors, and a variety of other uses. Axial disks are pressed in the axial direction, and if a hole is desired, one can be incorporated as a post in the pressing die. The anisotropy of an MQ3 axial disk is imparted mechanically via hot plastic deformation during the pressing process, while anisotropy in sintered NdFeB requires incorporation of a solenoid within the die to combine field alignment with pressing.

Another simple anisotropic NdFeB magnet to manufacture is the rectangular block shown in Figure 3. With sintered NdFeB, the aligning field can be parallel or perpendicular (transverse) to the pressing direction. Although higher energy



2 Axially oriented disk magnet (a); axially oriented donut (b).

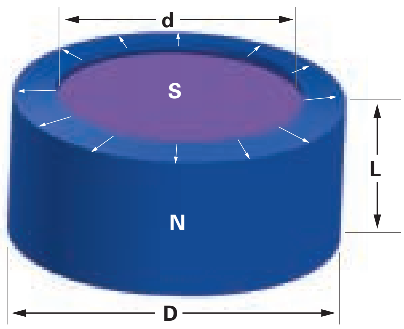




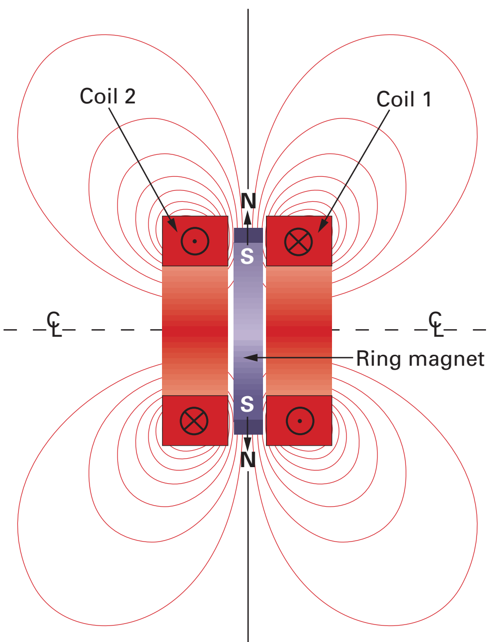
3 Rectangular block magnet oriented through thinnest dimension.

products can be attained via transverse-field pressing, most sintered NdFeB rectangular blocks for linear motors must be pressed under a parallel alignment field because they tend to be oriented through their thinnest dimension. The pressing process for MQ3 blocks is much simpler because MQ3 requires no aligning field during fabrication. Some linear motor designs require a mechanical feature, such as a hole or a step, for assembly purposes. These can usually be incorporated into the pressing die.

The most difficult anisotropic NdFeB magnet to manufacture is a radially oriented ring (Figure 4). The radial aligning field required when pressing a sintered NdFeB ring is extremely difficult to generate. As Figure 5 shows, placing two axial solenoids in opposition, such that their fields buck each other and are forced radially outward, usually creates this magnetic field. Pressing radially-oriented, sintered NdFeB rings is further complicated by the fact that these bucking solenoids must be incorporated into the pressing die.



4 Radially oriented ring magnet.

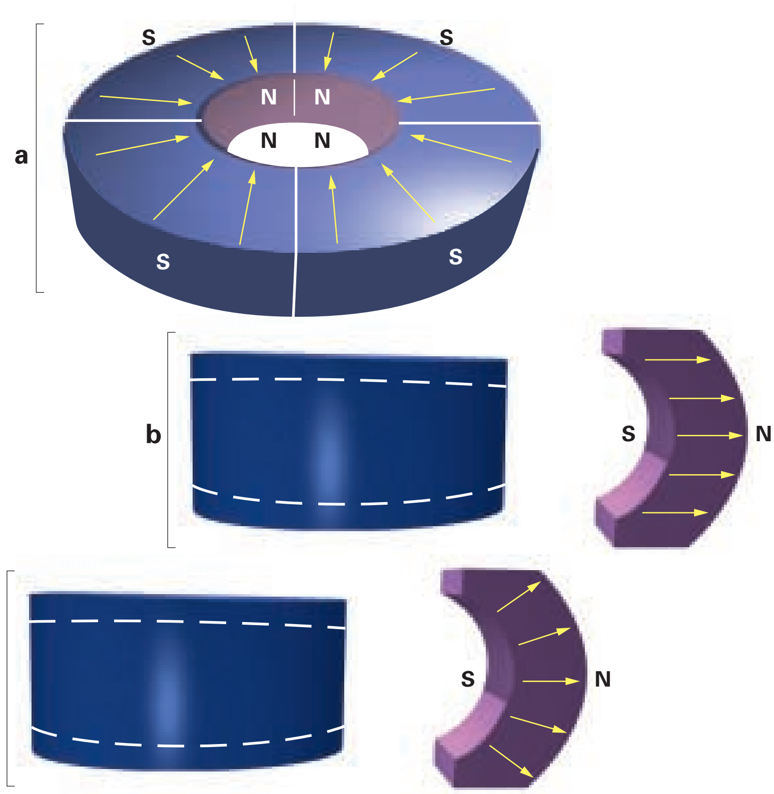


5 Opposing solenoids creating a radial orienting field for aligning ring magnets.

Fabricating a radially oriented MQ3 ring is much simpler. The MQ2 "preform" magnet is extruded to create a long, thin-walled ring. No aligning magnetic field is required in making MQ3 rings. Still, their manufacture is somewhat wasteful because approximately one-third of the extruded form must be removed so that the useable magnet ring has homogeneous magnetic properties.

In many cases, it's most advantageous from a cost perspective to fabricate radially oriented rings from isotropic MQ1 or MQ2. Such rings are frequently used in rotating DC motors, and their price is significantly lower than that of sintered NdFeB or MQ3 rings.

Another alternative to radially oriented rings is to approximate the ring with a series of arc segments. In fact, arc segments may be required in instances where the ring's annular thickness is large. As shown in Figure 6, such arcs can either be tight-fitting segments glued together (more expensive, higher performance) or isolated individual arc segments (less expensive, lower performance). There are limitations on the maximum arc angle that can be manufactured in anisotropic NdFeB, and while sintered NdFeB arc segments tend to have parallel orientation, MQ3 arcs achieve much closer to true radial orientation. Arc segments will usually yield a lower motor performance than complete radially ori-



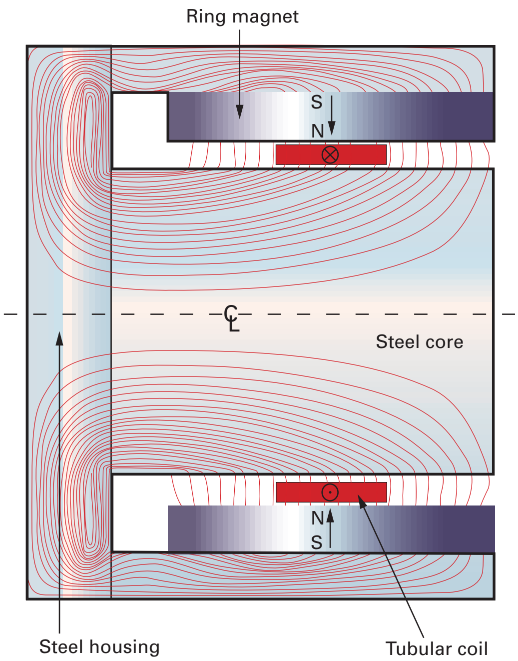
6 Thick radial ring composed of tight-fitting arc segments (a); individual sintered NdFeB motor arc segment with parallel orientation (b); individual MQ3 motor arc segment with radial orientation (c).

ented rings, though an array of MQ3 arcs will result in a much closer approximation to a full ring than an array of sintered NdFeB arcs.

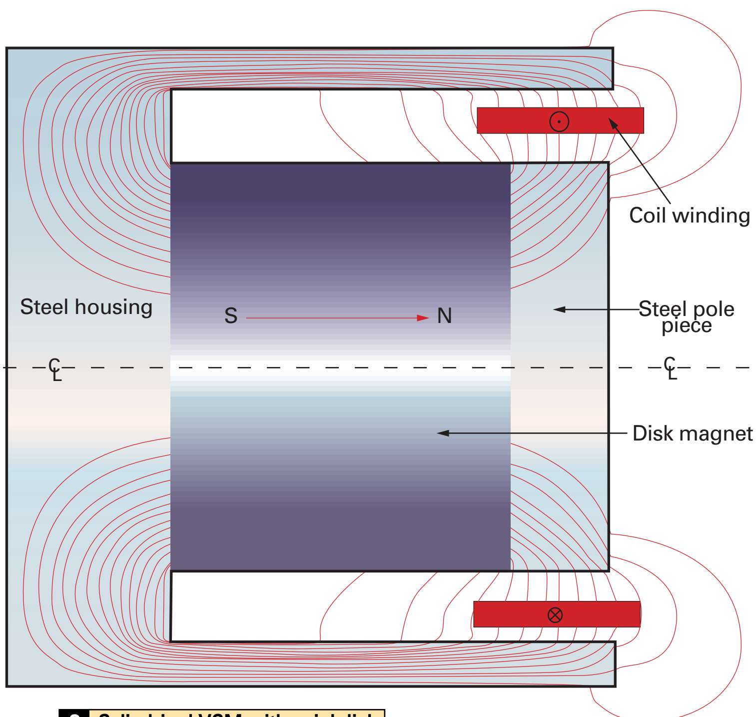
Linear Motor Designs: Non-Commutated

Voice Coil Motors (VCM)

The most basic form of a direct-drive linear motor is the voice coil actuator, or voice coil motor (VCM). VCMs are limited-motion electric motors. They employ a stationary permanent magnet field assembly in conjunction with a moving coil winding assembly to produce a force proportional to the current applied to the coil. These two-terminal, non-commutated, single-phase electromagnetic devices are used in linear motion applications requiring high acceleration, high frequency actuation, and flat force vs. displacement output. Voice coils provide cogging-free, hysteresis-free motion capable of extremely fine position sensitivity, limited only by the feedback sensor used to close the control loop.



7 Cylindrical VCM with radial ring.



8 Cylindrical VCM with axial disk.

Because the moving coil assembly is completely non-ferromagnetic, the working air gap for a VCM's magnetic circuit is quite large, and the magnet must operate at a low load line (typically 1.0–2.0). NdFeB magnets are the obvious choice for high-performance VCMs: their high energy product and stiff intrinsic coercivity allow high magnetic flux densities to be pushed across these large air gaps, while withstanding the demagnetizing fields generated by the VCM's coil windings.

In its simplest form, a linear VCM is a tubular coil of wire situated within a radially oriented DC magnetic field (Figure 7). In this particular geometry, the magnetic field is produced by a radially magnetized permanent magnet ring (such as that shown in Figure 4) embedded within the inside diameter of a steel back-iron cylinder. Typically, the ring magnet would be an isotropic MQ1 or MQ2, though an anisotropic MQ3 ring might be required for higher-force applications. An inner steel core set along the axial centerline of the coil, joined at one end to the permanent magnet assembly, is used to complete the magnetic circuit.

When current is applied to the circumferentially wound coil, it interacts with the radial magnetic field of the permanent magnet assembly via the Lorentz Force Principle to create an axial force (i.e., mutually perpendicular to the vectors of the current flow and the magnetic field) between the coil and magnet assemblies. The polarity of the current-producing voltage applied to the two terminals of the coil dictates the direction of the force upon the coil. The working air gap of the magnetic circuit is axially quite long, roughly equivalent to the axial length of the NdFeB magnet ring. The air gap magnetic field is usually in the range of 0.4–0.6 times the remanence (B_r) value of the magnet material employed.

Figure 8 shows a second version of the cylindrical VCM. This design employs an axially magnetized disk (or donut), such as that shown in Figure 2. The magnetic field is bent radially outward through a steel pole piece and across the working air gap (through the coil winding). The outer steel housing then closes the magnetic circuit. The same VCM principles of operation described above also apply to this geometry. The working air gap of this magnetic circuit is axially much shorter than in Figure 7's design, but the air gap magnetic field is significantly stronger: usually in the range of 0.6–0.9 times the magnet material's B_r. Further, while the axial disk is the most easily manufactured magnet shape for the highest-energy NdFeB grades: sintered NdFeB and MQ3, this isn't the case with the radial rings of Figure 7's VCM.

Another very common VCM form is rectangular (rather than cylindrical) in cross-section (Figure 9). This design uses rectangular block magnets mounted to two outer steel field plates, with a central steel core splitting the magnetic circuit in half. The coil is wound such that it encloses, but doesn't touch, the central core, and the coil rides along the two air gaps between the magnets and the core. This design is suitable for long stroke applications—perhaps up to four inches. MQ3 and sintered NdFeB are usually the magnets of choice because the rectangular block geometry is easily fabricated. The tightest tolerance—the magnetic length—is in the pressing direction, which may allow for the use of an as-pressed MQ3 block with no secondary operations required. The air gap magnetic field is usually in the range of 0.4–0.6 times the magnet's B_r.

Figure 10 shows another variation of the rectangular VCM. This magnetic circuit uses two sets of alternating-polarity rectangular block magnets mounted to outer steel field plates. There's no central steel core. The coil is wound in a "racetrack" configuration, riding in the air gap formed between the magnet surfaces. This VCM design is better suited for short-stroke, high-force applications, and, for the same reasons as described above, MQ3 and sintered NdFeB are usually the magnets of choice. The air gap magnetic field is usually in the range of 0.4–0.7 times the magnet's B_r.

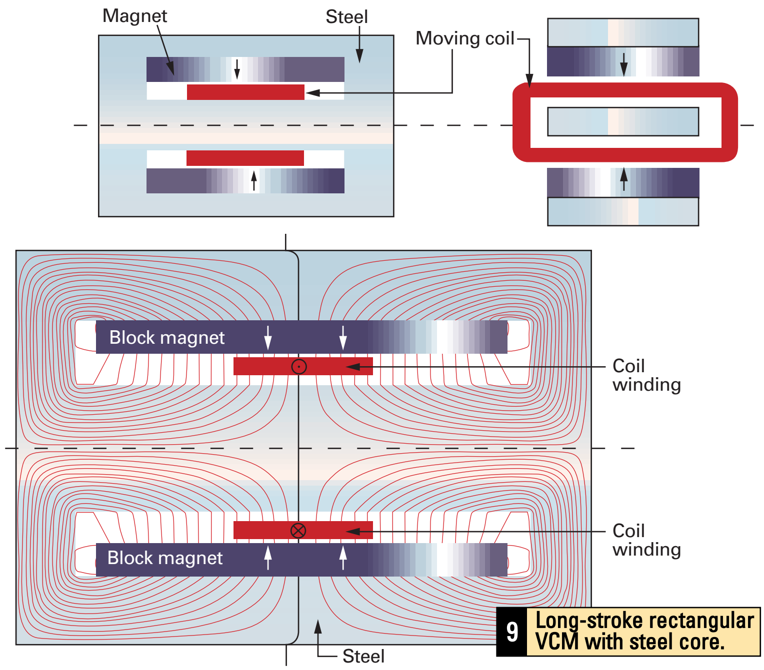
Unlike the cylindrical VCMs, which fully utilize all 360° of the coil winding, the rectangular designs have "end turns" that aren't linked by the permanent magnets' flux. This usually implies that, for a given-volume linear motor (and a given magnet volume), a cylindrical design will be more efficient than a rectangular one.

Moving Magnet Actuators (MMA)

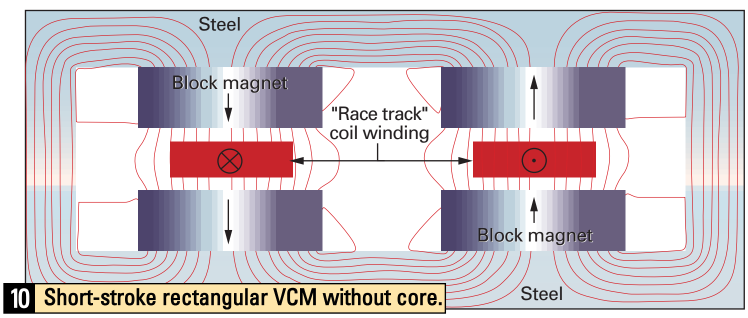
The MMA is somewhat of an inverted VCM. Like voice coils, MMAs are direct drive, two-terminal, non-commutated, single-phase, limited-motion electric motors. They employ a moving permanent magnet field assembly and a stationary coil winding assembly to produce a force proportional to the current applied to the coil. Usually, MMAs are of cylindrical cross-section.

Figure 11 shows a commonly employed MMA magnetic circuit. Two radially-oriented NdFeB rings of opposite polarity are mounted on a central steel core. Within an outer steel shell are two coils, wound in series opposition, which couple with the permanent magnets' fields to produce an additive axial force. The two radial ring magnets can be replaced with a single axial disk (Figure 12) for a more economical use of the higher-energy varieties of NdFeB. For an MMA, the air gap magnetic field is usually in the range of 0.4–0.7 times the magnet material's B_r.

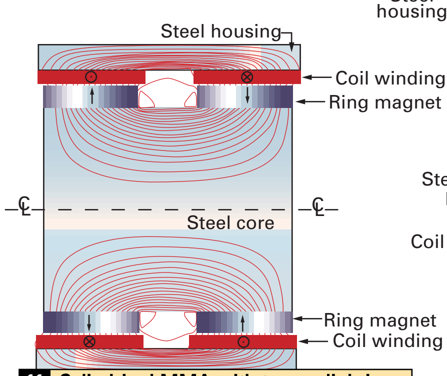
Unlike VCMs, MMAs exhibit cogging forces and off-axis bearing loads because of attractive forces between the coil and field assemblies. They also have greater eddy current and hysteresis losses than VCMs. Their advantages are that the coil is well heat sunk by the steel housing and there are no moving coil leads. MC



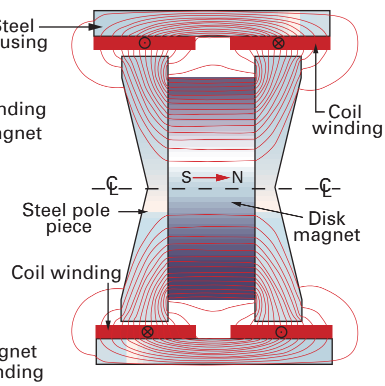
9 Long-stroke rectangular VCM with steel core.



10 Short-stroke rectangular VCM without core.



11 Cylindrical MMA with two radial rings.



12 Cylindrical MMA with single axial disk.

Make Contact!

Anthony C. Morcos is a senior applied scientist for the Magnequench Technology Center. He is responsible for the design and analysis of various permanent magnet devices, including motors, actuators, and sensors. Contact him at 9000 Development Drive, P.O. Box 14827, Research Triangle Park, NC 27709-4827; tel: (919) 993-5510; fax: (919) 993-5501; amorcos@mqii.com; www.magnequench.com.

Editor's Note:
Next issue, we'll continue to explore the impact high-energy permanent magnets have made on linear motors.