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A Primer on Magnetic Circuit Design: Materials, Permeance Calculations, and Finite Element Analysis

Circuit Design, Magnetic

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I. Introduction

This introduction to electromagnetics is intended to de-mystify magnetic circuit design, because beyond the complicated integral and differential equations associated with this science lies a vital and interesting discipline. Electromagnetics provides the world with gadgets as simple as refrigerator magnets to systems as complex as nuclear accelerators and magnetic resonance imagers. This article provides engineers with the basic considerations of magnetic circuit design, especially as applied to electric motors and voice coil actuators.

The first section explores the three fundamental types of magnetic materials: permanent magnets, permeable steels, and magnet wire. The salient magnetic properties which characterize magnets and steels are discussed to help explain the differences between and the applications of various material types. Magnet wire, a simple and often overlooked magnetic circuit component, is also discussed.

The second section discusses basic electromagnetic design techniques. Because Maxwell's Equations form the foundation of all electromagnetic theory, their presentation is required. The remainder of this section is devoted to demonstrating how the direct use of Maxwell's Equations can be avoided: namely, through permeance calculations and finite element analysis. The article concludes with an analysis of an actual design and shows how the aforementioned materials and design techniques are applied to a real application. The design example is a linear voice coil actuator used to control a small valve.

Quantity	Symbol	MKS	CGS	English
Flux Density	B	Webers/m^2	Gauss	Kilo-Lines/in^2
Magnetic Field	H	Amps/m	Oersted	Amps/in
Magnetic Flux	ϕ	Webers	Maxwells	Kilo-Lines
Force	F	Newtons	Dynes	pounds-f
Energy	W	Joules	Ergs	Ft.-Pounds

Figure 1 - Electromagnetic Unit Systems

II. Magnetic Materials

Nearly all types of magnetic circuits can be divided into three basic material groups: magnets, steel, and wire. The distinctions between these classifications, especially between magnets and steel, are often blurry. It is, therefore, necessary to describe how the magnetic properties of such materials are defined. Then it is possible to differentiate between the wide variety of available materials and to determine which material is best suited to a particular application.

Figure 1 is a description of the three different unit systems which are most commonly employed in electromagnetic design and analysis. An electromagnetic engineer should be able to use all three interchangeably.

II-A Permanent Magnets

Figure 2 shows a somewhat idealized second-quadrant demagnetization

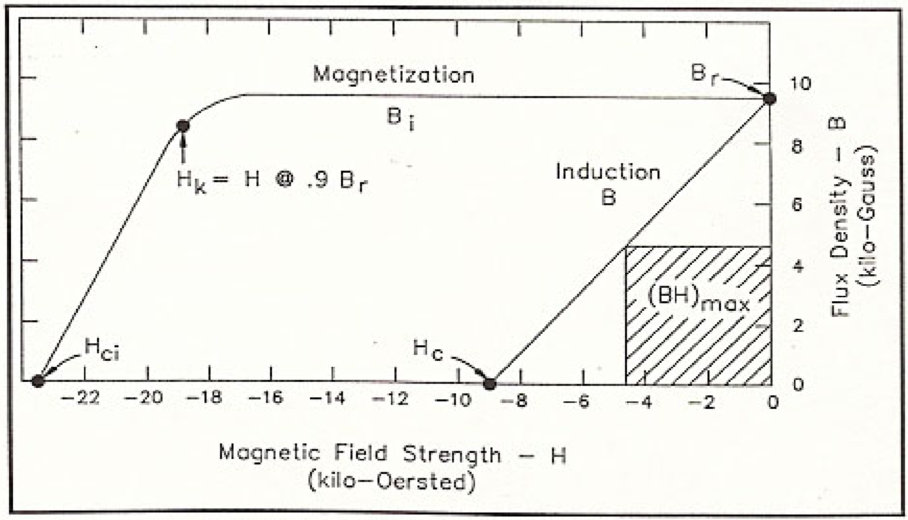


Figure 2 - Permanent Magnet B vs. H and B_i vs. H Curves - Idealized

curve, also called a hysteresis loop, for a permanent magnet. Both the induction (normal) curve and the magnetization (intrinsic) curve are shown. These curves are inter-related (B_i=B-H) and are actually two different ways of conveying the same information, though the intrinsic curve shows more information in the second quadrant. The hysteresis loop defines the magnetic properties of a permanent magnet. Of particular interest are the quantities B_r, H_c, BH_{max} and (to a lesser degree) H_k.

The remanent flux density, B_r, is a measure of the flux-producing capability of the magnet material. The normal and intrinsic coercive forces, H_c and H_{ci} respectively, determine the amount of external opposing field a magnet can withstand without demagnetizing: i.e., its "magnetic hardness". The knee field, H_k, is the amount of external demagnetizing field to which a magnet can be exposed without permanent performance degradation. The maximum energy product, BH_{max}, is a figure of merit for a permanent magnet material such that a higher BH_{max} yields a minimum volume of magnet required to supply a given flux density in a given working gap.

Figure 3 describes, through their second quadrant B vs. H curves, some of the more commonly-employed permanent magnet materials: Alnico 8, barium ferrite, and the sintered rare earth-transition metal alloys $SmCo_5$, Sm_2Co_{17}, and $Nd_2Fe_{14}B$.

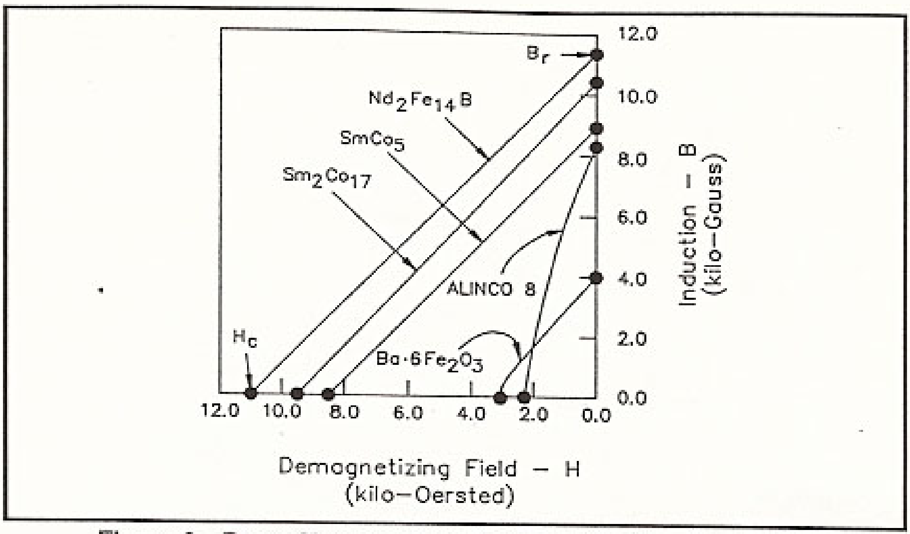
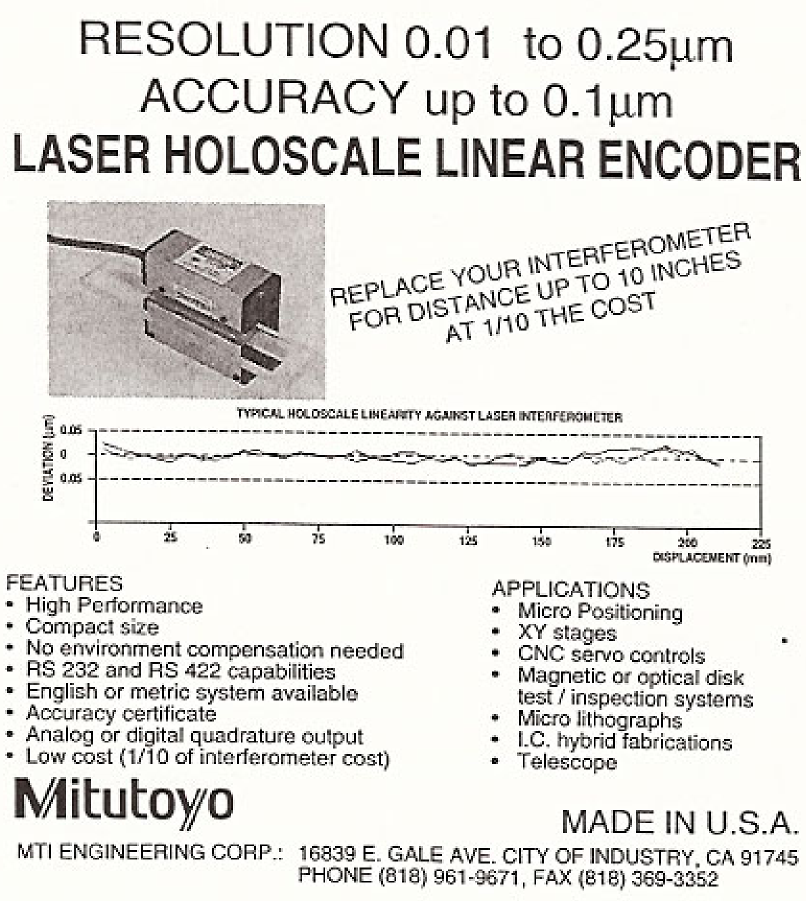


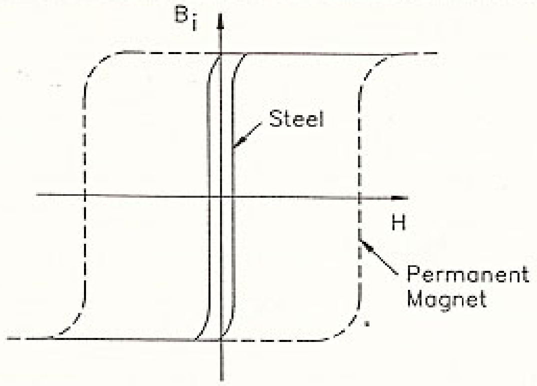
Figure 3 - Room Temperature Demagnetization Curves for Commonly -Used Permanent Magnet Materials

Alnico is a low cost alloy of aluminum, nickel, and cobalt, and Alnico 8 is a popular grade of this alloy. It has excellent temperature stability and is quite easy to magnetize. Permanent magnets are fabricated unmagnetized and must be magnetized either by the vendor or the end user. Alnico 8 is also easy to demagnetize, by virtue of its low coercive force, and must operate at a high permeance (B/H). Some uses of Alnico include holding magnets and bias magnets for sensitive instruments which must exhibit stability over a wide temperature range.

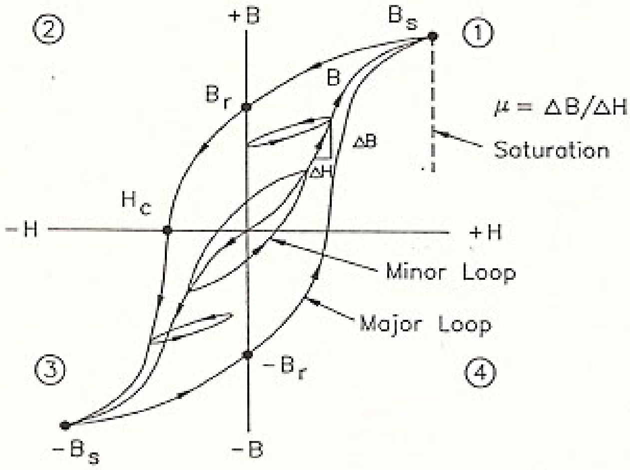
Barium ferrite is a type of ceramic which was the original "square loop" permanent magnet: H_c in Oersted nearly equals B_r Gauss. Strontium ferrite is another type of ceramic magnet with similar properties to barium ferrite. Ceramic magnets are fairly easy to magnetize and demagnetize and are somewhat brittle mechanically. Ferrites are ideal for high-volume, low-cost, low-performance applications by virtue of their low piece-part cost and high tooling cost. Common applications for ceramics are in loudspeaker voice coil actuators and in DC motors for appliances.

$SmCo_5$ was the first commercially-available high-energy rare earth magnet material. It is a sintered alloy which is extremely brittle and quite difficult to magnetize and demagnetize. Its temperature stability is not as good as Alnico 8, but it can operate at temperatures as high as 250° C under certain operating conditions. Sm_2Co_{17} is a newer, higher-energy alloy which seems to be replacing $SmCo_5$ for most magnet manufacturers. Samarium-cobalt magnets are extremely expensive per unit weight, but this is somewhat offset by their high energy product which allows for a much smaller magnet volume to provide the necessary flux. Such magnets are difficult to fabricate in non-standard shapes and must be ground, in an unmagnetized state, to final dimensions. These factors strongly influence the design of magnetic circuits employing such magnets. Applications for samarium-cobalt magnets include gyroscopes, electron beam focusing structures in devices such as traveling wave tubes, and motors designed to operate at temperatures above 135° C.





a) Difference Between Steels And Permanent Magnets.



b) B vs. H Characteristic Curve For A Soft-Magnetic Material.

Figure 4 - Soft Magnetic Steels

$Nd_2Fe_{14}B$, or neo-iron, is the newest, highest energy magnet material available. It is lower in cost than samarium-cobalt because iron is much cheaper than cobalt and neodymium is more plentiful than samarium. This material is prone to oxidation and exhibits extreme temperature instability: it is wise to operate neo-iron below 100° C. Still, an increasing number of commercial applications are employing this material. Neo-iron is replacing ferrite as the magnet of choice for automotive motor applications (e.g., starter, windshield wiper, power window motors) because the miniaturization afforded by its higher energy product can greatly reduce the overall weight and increase the fuel efficiency of an automobile.

II-B Soft-Magnetic Steels

Figure 4a shows how the hysteresis loops of magnetic steels (also known as soft-magnetic or back iron materials) are different than those of permanent magnets (also called hard-magnetic materials). Figure 4b shows a typical B vs. H curve for a soft-magnetic material. Of particular interest are the quantities B_s, B_r, H_c and mu. The saturation flux density, B_s, is an indication of the flux-carrying capability of the material. B_r for steel indicates its amount of magnetic retentivity when all external fields are removed, and H_c indicates the amount of external field required to overcome this magnetic retentivity. B_r and H_c are usually undesirable properties in steel and should be minimized. The permeability, mu, is the slope of the B vs. H curve: a higher permeability implies better efficiency in carrying magnetic flux.

Vanadium Permendur (VP) has the highest saturation flux density (B_s = 24.0 kG) of all magnetic steels, allowing for minimum weight of the soft- magnetic members. This alloy of vanadium, cobalt, and iron is exorbitant in price, extremely difficult to machine, even more difficult to procure, and is very sensitive to thermal and mechanical stresses. These properties imply that VP is used primarily in airborne and spaceborne applications, where the payload reduction afforded by the use of this material in an electromagnetic device overcomes the added cost of this material. Unlike many other soft-magnetic iron alloys, vanadium permendur does not readily oxidize and, therefore, requires no corrosion protection.

Cold-rolled steel (CRS) saturates at 20.7 kG, therefore requiring approximately 15% more back iron volume (and mass) to carry the same amount of flux as VP. CRS is reasonable in cost, easy to obtain, and readily machined. Unfortunately, it must be plated to prevent rusting: this plating can present difficulties in manufacturing, such as holding extremely tight tolerances, and in the deep space vacuum environment, where potential flaking of the plating can be disastrous.

400-series stainless steel (416SS) saturates at 16.8 kG, leading to a 30% increase in back iron weight compared to VP. it is relatively inexpensive, easily obtained, and is considerably easier to machine than VP, though somewhat less machinable than CRS. The primary advantage of 416SS is that it requires no plating or protective coating to avoid oxidation. (Remember that 300-series stainless steel is non-magnetic and should not be employed in magnetic flux carrying members of an electromagnetic device).

The aforementioned soft-magnetic materials are used primarily in DC magnetic circuits where the back iron is not being cycled through its hysteresis loop. In most motor designs, the armature steel is being cycled, and a high permeability and low H_c are desirable to maximize efficiency. Motor armatures are also usually laminated to reduce eddy current losses. There are many grades of silicon steel, such a M19, which have been especially formulated for AC magnetic circuit designs, such as motors and transformers. These alloys, when properly heat-treated, have a high permeability, a low coercive force, and a saturation flux density nearly equal to CRS. The silicon steel alloys are primarily available in sheet stock form to best allow for the fabrication of motor and transformer laminations.

II-C Magnet Wire

Magnet wire is the most simple of the magnetic materials to describe. Of primary interest are: the conductor material and its resistivity, the wire geometry, and the insulation type. The primary conductor materials employed in magnet wire for motors and voice coil actuators are solid copper, solid aluminum, and copper-clad aluminum. The most common is copper wire, which is easy to wind and is readily soldered onto lead wires or terminal pins. Aluminum wire is one-third the weight of copper wire, though it has 1.6 times greater resistivity than copper. Thinner gauges of aluminum wire tend to be quite brittle and tough to work with. It is also difficult to terminate aluminum wire because it does not solder well: solder joints with aluminum wire are prone to corrosion and are inherently unreliable. Cladding

MKS Unit System

electric field intensity	E	volt/metre
magnetic field intensity	H	ampere/metre
electric flux density	D	coulomb/metre^2
magnetic flux density	B	tesla
electric current density	J	ampere/metre^2
electric charge density	P	coulomb/metre^3

The Maxwell relations may be cast in ~~different~~ differential form thus:

$\nabla \times E = \partial B/\partial t$ $\nabla \times H = J + \partial D/\partial t$ $\nabla \bullet D = P$ $\nabla \bullet B = 0$

To these differential relations are added the constitutive relations:

$D = \varepsilon E$ $B = \mu H$ $J = \delta E$

Figure 5 - Maxwell's Equations - Differential Form -

aluminum wire with a thin layer of copper can reduce the termination difficulties, but the mechanical brittleness of this wire is still a manufacturing problem which must be considered.

Round cross-section is the most common wire shape because it is easy to manufacture, insulate, and wind. Square or rectangular wire is employed in layer-wound coils, such as those in voice coil actuators and wound inductors, where maximum conductor density is required. A performance enhancement of seven to 10% is potentially attainable with rectangular wire compared to round wire because of the increased fill factor of conductor within the winding volume. Such wire cannot be twisted and is prone to dielectric breakdown when wound around corners, implying a reduced reliability compared to round wire.

Magnet wire must be electrically insulated to prevent turn-to-turn shorts in a coil winding. A wide variety of polymeric insulation types with thermal ratings from 105 degrees C (e.g., Polyurethane) to 220° C (e.g., Polyimide) are available. Aluminum wire can be anodized, with the resulting insulating layer of aluminum oxide rated to 500° C. Factors affecting the choice of wire insulation include cost, exposure of the winding to chemicals, outgassing characteristics in a vacuum environment, wire bonding and soldering techniques, required dielectric strength, and operating temperature.

III. Electromagnetic Design Techiques

Maxwell's Equations form the foundation upon which electromagnetic theory is based. Figure 5 presents these equations in their differential form, though they can also be expressed in integral form.

Once the electromagnetic design engineer masters the endless manipulations and contortions of Maxwell's Equations, he or she can then concentrate on simplifying these complex differential equations into more-easily-solved algebraic equations. Figure 6 describes the most basic simplification technique: the analogy between electrical and magnetic circuits. The fundamental flaw in this analogy is that electricity is contained within wires and flows very nicely between circuit elements, while magnetic fields tend to leak from their steel "wires" and fill all of space. If a magnetic circuit design is efficient, the ratio of the useful air-gap flux to the wasted leakage flux is very large. In such a design, the analogy is useful.

A fine-tuning of the electrical/magnetic circuit analogy leads to the "method of permeances" technique, where the permeance (similar to electrical conductance) of various flux paths in and around the device are calculated and combined in series and/or parallel. Most electromagnetic engineers have a handy chart of permeance formulae for a wide variety of flux leakage path geometries. Using this method, the magnetic circuit designer can obtain rather accurate results using just paper, a pencil, and a scientific calculator, especially if he or she can accurately estimate the flux leakage paths.

When more accurate or more detailed performance estimates are required, the use of finite element analysis (FEA) is recommended. FEA is a method by which the geometry of a magnetic circuit is modeled on the computer by breaking it up Into thousands of tiny pieces (elements), each of which is bounded by points (nodes). Based upon the material properties and boundary conditions input by the user, the computer approximates the solution to Maxwell's Equations at each point. By combining each individual point solution, a detailed magnetic field profile can be calculated over the entire model. The FEA technique, increasingly practical because of the ever higher power, faster speed, and lower cost of computers, has become an indispensable tool in the arsenal of the magnetic circuit designer.

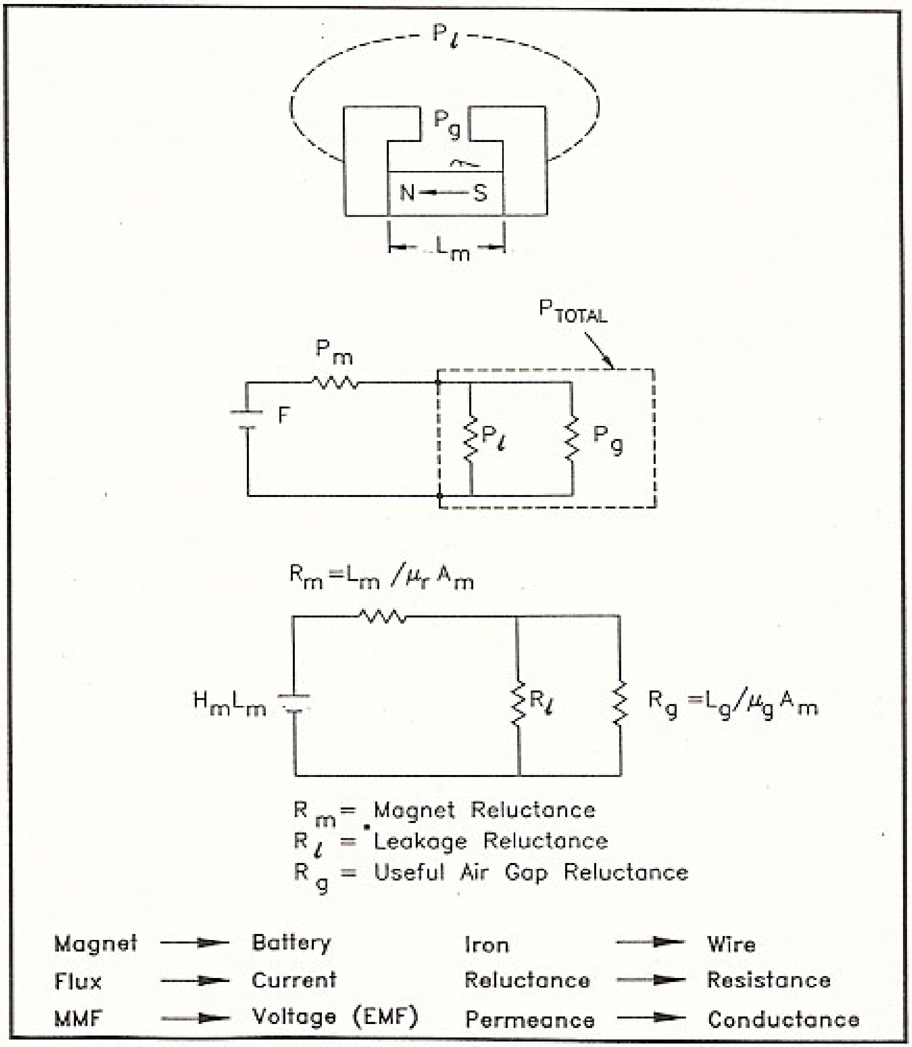


Figure 6 - Analogy Between Electrical and Magnetic Circuits

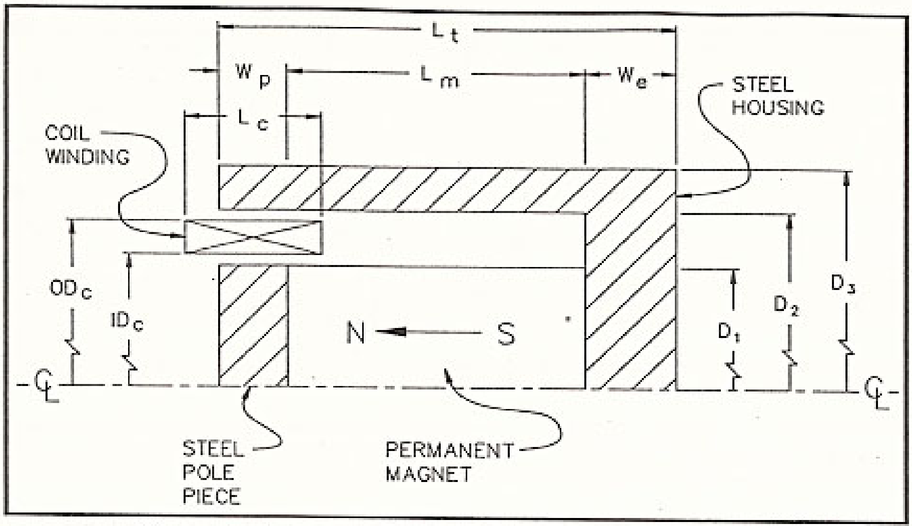
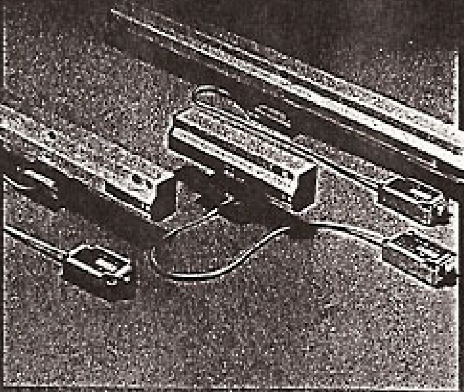


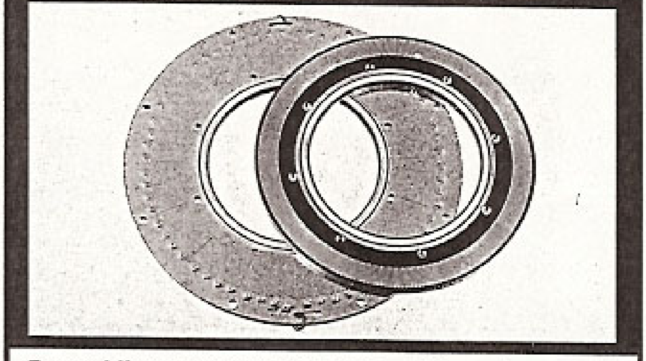
Figure 7 - LA06-08-000A Linear Voice Coil Actuator - Magnetic Circuit Diagram -

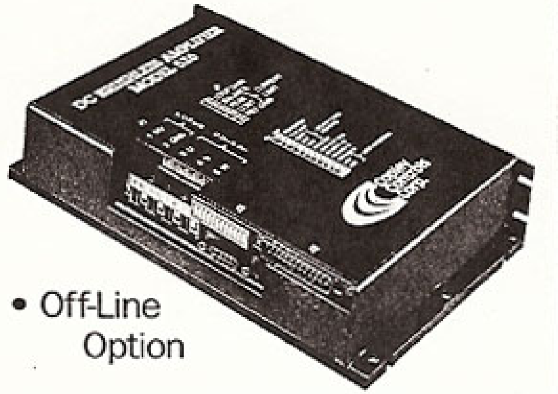
There are several commercial FEA software packages designed to solve two-dimensional, axi-symmetric, and three-dimensional electromagnetic problems. Though many can be run on personal computers, these computation-intensive codes are best suited for more powerful machines such as workstations and mini-computers, especially in the modeling of three-dimensional problems. The author has tried most of the available codes, and, when properly used, all seem to provide fairly accurate results when applied to two-dimensional and axi-symmetric DC magnetic circuits. The differences between FEA programs become apparent when comparing their ease of use, their three-dimensional capabilities, and their handling of more complex mathematical problems, such as eddy-currents and transient response of multi-phase motors and multi-frequency EM wave propagation in waveguides.

Before jumping head first into FEA, it is vital that the magnetic circuit designer have a solid understanding of the problem at hand. Rough hand calculations should be performed in preparation for any computer modeling. Computers are quite capable of yielding wildly inaccurate, yet perfectly believable results due to simple but unnoticed errors on the part of the modeler: even the most sophisticated FEA programs cannot detect all potential user errors (e.g., the use of diameters instead of radii in an axi-symmetric geometry).

It should also be noted that three-dimensional FEA is perhaps ten times more complex than two-dimensional or axi-symmetric analysis. It is often possible to approximate a 3-D solution through the careful interpretation and combination of several 2-D models. When 3-D FEA is absolutely required, the magnetic circuit designer must have the following available: a reasonably-powerful computer (a good workstation as a minimum); a large color monitor; a lot of time and patience; and the fortitude to deal with a potential cross-eyed condition brought about by trying to visualize the 3-D problem on a 2-D computer screen.







IV. Sample Design

A Linear Voice Coil Actuator

The following example is presented in order to demonstrate how the aforementioned magnetic materials and design techniques are applied to a real device. The unit under study is a linear voice coil actuator, part number LA06-08-000A, which was designed by BEI for use in a valve control application.

Figure 7 shows a cross-sectional diagram of the magnetic circuit for the linear voice coil actuator. Figure 8 describes how the theory of operation for a voice coil actuator is based upon the Lorentz Force Equation, which can be derived from Maxwell's Equations.

The design process for any electromagnetic device follows roughly the same path. It Is assumed that the designer is familiar with the equations which govern the performance of the device in question. First, the customer's footprint, environmental, performance, and cost requirements for the application must be defined as thoroughly as possible. Based upon these specifications, the materials to be used in the design are chosen. Then, first-cut permeance calculations allow for a ball park performance estimate. Subsequent refinements of the permeance formulae, which can be incorporated into a BASIC or FORTRAN computer program for rapid iterations, can lead to a more optimized magnetic circuit design with better performance estimates. The "permeance" design is then modeled on FEA and refined further, if necessary. Engineering drawings are created to reflect the final FEA design. The unit is then built and tested to "close the loop", with any discrepancies between the calculated and measured performance being duly accounted for in subsequent permeance and FEA calculations.

Figure 9 shows the performance, footprint, and environmental specifications which define the requirements for the valve control linear actuator. Evaluation of these requirements led to the following material choices: neo-iron magnets, cold-rolled steel back iron with zinc plating, round copper wire (AWG #37) with polyurethane insulation, and a wound paper coil bobbin.

As shown in Figure 7, the magnetic circuit chosen for this application has an axi-symmetric geometry, employing a solid cylindrical magnet with a pole piece attached to one end. The magnet/pole piece assembly is inserted into a steel housing with one open end and one closed end. The magnetic flux emanates from the north pole of the magnet and turns radially outward through the pole piece, across the working air gap, and into the steel housing. The flux then flows axially along the diameter of the steel housing towards its closed end, returning to the magnet's south pole. The coil is wound circumferentially and is placed in the working air gap as indicated. Based upon the direction of current flow in the coil, an axial force to the left or the right is generated.

The permeances of the various elements of the magnet circuit (i.e., the air gap, the pole piece, the walls of the steel housing, and the various flux leakage paths) are then estimated. It is assumed that the magnet is a source of magneto-motive force (mmf), with its own internal reluctance. Using the analogous DC electrical circuit as a model, the magnetic circuit equivalent is developed, and the magnetic flux flowing in different circuit elements is estimated. Based upon their permeances, the flux density in the circuit elements can be calculated. Then their dimensions are modified to obtain the desired air gap flux density and to avoid over-saturation and under-utilization of the steel.

An appropriate coil winding must also be designed to meet the voltage and current capabilities of the customer's power supply. The coil and its bobbin must fit within the working air gap, while having adequate mechanical clearances in the radial direction (to avoid rubbing) and in the axial direction (to meet the stroke requirement). The maximum number of ampere-turns generated by the coil winding must be kept low enough to prevent damage to the permanent magnet through "arma-

Lorentz Force

$\bar{F} = Q(\bar{E} + v \times \bar{B})$ $\bar{F} = \int I d\bar{L} \times B$

$F = B\,I\,L$: assuming $B \perp I$; L= wire length threading B

$K_F = F/I = B \bullet L$ $K_F = B_g\,(N)\,(MLT)$

English Units

$K_F = 2.78 \bullet 10\text{-}4\,(B_g)\,(D_m)\,(N)$: applies to cylinderical geometry

$K_A = K_F/\sqrt{R}$: Figure of merit for vouce coil actuator;

indication of electrical to mechanical energy conversion efficiency.

Notes: Lorentz force > L= wire length threading B K_F = force constant

B_g = gap flux density N= number of turns L = mean length of turn

Note: English Units >

K_F = #/A B = klines/in^2 D_m = mean coil diameter, inches $K_A = \#/\sqrt{W}$

Figure 8 - Linear Voice Coil Actuator - Theory of Operation

I. Footprint:
- A. Cylinderical geometry, open at one end
- B. Max. outer diameter = 0.625"
- C. Max overall length (fully extended) = 1.000"

II. Environment:
- A. Max. ambient temp. = 35° C
- B. Max. operating temp. = 85° C
- C. Actuator will be in a sealed enclosure with no exposure to liquids or dirt, no air cooling.

III. Performance:
- A. Operating voltage = 10-12 V
- B. Max. current = 1.0 A
- C. Active stroke = ±0.075"
- D. Total Mechanical Travel = ±0.100"
- E. Peak Force = 4.0 oz
- F. Max Duty Cycle = 10%
- G. Coil Assy. Weight = minimized

Figure 9 - Valve Control Linear Voice Coil Actuator
- Customer Specifications -

ture reaction": the magnetic field generated by the coil via the right-hand-rule which tends to aid or oppose the magnet's field, depending upon the direction of current flow.

After several permeance calculation iterations of magnet, steel, and coil dimensions, a satisfactory design is attained and modeled (axi-symmetric) on FEA for verification and fine tuning. First, the geometry outlines of the various magnetic circuit elements and the surrounding air boundary are drawn. This geometry is then divided into points (nodes) which define triangles and rectangles (elements). The electromagnetic properties of the magnets, steel, and copper are defined via constants and non-linear B vs. H curves, if necessary. The boundary conditions, which can be determined from Maxwell's Equations (see Figure 5), must also be established. The current load, in ampere-turns, through the coil must be defined. The user defines the job control parameters: nonlinear or linear analysis, number of iterations, solution convergence criteria, etc.

The FEA software then assembles a set of huge matrices, taking into account the geometry, the material properties, the applied currents, and the boundary conditions, to represent the 2nd order partial differential equation (based upon Maxwell's equations) defining the problem. The computer will iteratively solve the matrix equation, yielding a magnetic potential at each node in the model. Armed with these magnetic potentials, the magnetic circuit designer can calculate more detailed information about the design, such as flux density contours and values anywhere within the model, forces on the coil, coil inductance, and flux leakage paths.

Figure 10 shows an FEA flux line plot for the LA06-08-000A linear voice coil actuator: the flux paths are very clearly defined. The analysis confirmed to within a few percent the flux density and force values predicted by the permeance calculations. The FEA model can be modified easily during the mechanical design process to account for manufacturing tolerances, assembly methods, material property variations, and different coil windings.

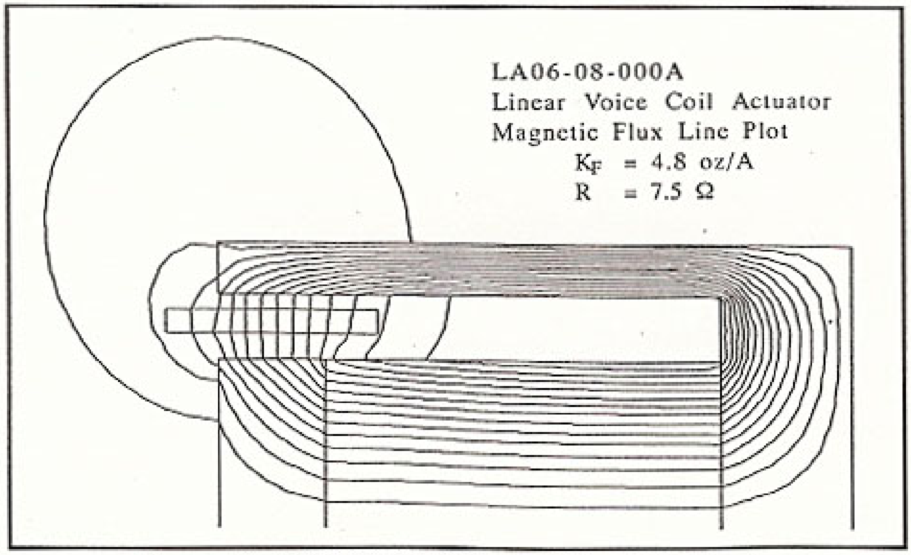


Figure 10 - LA06-08-000A Linear Voice Coil Actuator
- Magnetic Flux Plot -

The LA06-08-000A design presented above is a simplified example meant to give the reader a general idea of the overall magnetic circuit design process. The selection of a magnetic circuit configuration which best suits a particular application is the first step in the design process and is best performed by an experienced electromagnetic engineer. The detailed design, analysis, and manufacture of voice coil actuators and other electromagnetic devices can be an intricate process and is best left to those experienced in this field.

About the Author

Mr. Anthony C. Morcos is a Senior Magnetics Engineer for BEI Motion Systems's Kimco Magnetics Division. He joined the Kimco Magnetics Division in July, 1989. He is responsible for the design of linear and rotary actuators, magnetic bearings, and specialty magnetic devices. He also oversees the activities of the Kimco Magnetics Engineering Department.

Prior to joining BEI, Mr. Morcos was a Member of the Technical Staff at Hughes Aircraft Electron Dynamics Division in Torrance, California. There, he was responsible for the design, construction, and testing of millimeter-wave traveling wave tubes (TWT's). He also designed and analyzed advanced magnetic circuits for the focusing of electron beams. Prior to joining Hughes, Mr. Morcos was involved in graduate research at the University of Dayton, where he was an employee of the Magnetics Laboratory under the tutelage of Dr. Karl Strnat. There he participated in the development of rare-earth permanent magnet alloys. Under a U.S. Army Research Office Fellowship, Mr. Morcos worked at the U.S. Army Electronics Technology and Devices Lab, Fort Monmouth, New Jersey, where he worked with Dr. Herbert Leupold to design and analyze novel magnetic circuits for the bending and focusing of high-energy electron beams.

Mr. Morcos has a Master of Science in Electrical Engineering (honors) from the University of Dayton. He is a Member of IEEE and its Magnetics Society, as well as a Member of Tau Beta Pi. He is also the author of several papers on the design and analysis of magnetic circuits and the measurement of magnetic fields and forces.

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