Electromagnet Design Considerations

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Introduction

Oxford Learner's Dictionaries defines electromagnet as "a piece of metal that becomes magnetic when electricity is passed through it." Electromagnets are the embodiment of the physics fact that charged particles in motion (electric currents) produce and react to magnetic forces. Electromagnets usually consist of wire wound into a coil. Electromagnets are integral parts of common electrical devices, such as transformers, generators, motors, relays, etc., and are widely used in advanced technologies including particle accelerators, magnetic resonance imaging, proton therapy, mass spectrometers, magnetic levitation, e-mobility, and more.[1]

There are many ways to categorize electromagnets. One way is by the type of power source: there are DC, AC, and pulsed electromagnets. Another way is by the type of coil wires; there are traditional resistive and superconducting electromagnets. This article excludes superconducting electromagnets but focuses on traditional resistive electromagnets. Aspects of electromagnet design considerations will be presented in the below sections for a design engineers' reference. The article begins by a discussion on electromagnet core material's permeability and nonlinearity, as well as the residual field and its mitigation. The focus of the article then shifts to design techniques in creating highly uniform field or high strength field. Efficiency of magnetic designs is also discussed. The last aspect of the article covers safety considerations in electromagnet designs.

Core Material

Relative Permeability

Most electromagnets take advantage of a core - a ferromagnetic or ferrimagnetic metal component around which the electric wires are wound - to achieve higher magnetic field output[2]. The logic behind the core can be readily explained by the Ampére's circuital law. Ampére's circuital law relates the integrated magnetic field around a closed loop to the electric current passing through the loop:

$$\oint_C H \cdot dl = \sum I_f = NI$$

(Equation 1)

where H is magnetic field strength, N number of turns, and, I electric current in the coil. The above equation can be further transformed to the form of,

$$NI = \sum_i \Phi R_m = \sum_i \Phi \frac{l_i}{\mu_0 \mu_r S_i}$$

(Equation 2)

where Φ is magnetic flux in the closed magnetic circuit, Rm magnetic reluctance of the magnetic circuit segment i, li length of the magnetic circuit segment i, Si cross section of the magnetic circuit, μ0 permeability of vacuum (constant), and, μr relative permeability of the magnetic circuit segment i which is a unitless property. Since μr lands on the denominator in Eq. (2), it becomes obvious that utilizing higher relative permeability core materials has a direct effect on boosting magnetic flux, and therefore, magnetic flux density in the magnetic circuit.

A lot of electromagnets have an air gap, where the magnetic field is utilized and the work is done; for example, a hard disk drive read /write head setter electromagnet. Air's relative permeability can be considered as unity one - that makes it approximately equal to free space - but ferromagnetic and ferrimagnetic material can readily have relative permeability in the hundreds, thousands, or even hundreds of thousands.

The below table includes permeability values of some common materials. These are for reference only and should be used with caution because permeability varies greatly with field strength. And, at magnetic saturation point when the field strength is sufficiently high, any material's permeability trends toward 1.

TABLE I. PERMEABILITY OF COMMON MATERIALS[3]

Medium	Relative permeability, max., μ/μ0	Permeability, μ (H/m)	Magnetic field	Frequency, max
Vacuum	1, exactly	$1.25663706212 \times 10^{-6}$ (μ_0)		
Iron (99.95% pure Fe annealed in H)	200000	2.5×10^{-1}		
Permalloy	100000	1.25×10^{-1}	At 0.002 T	
Mu-metal	20000	2.5×10^{-2}	At 0.002 T	
Cobalt-iron (high permeability strip material)	18000	2.3×10^{-2}		
Iron (99.8% pure)	5000	6.3×10^{-3}		
Electrical steel	4000	5.0×10^{-3}	At 0.002 T	
Ferritic stainless steel (annealed)	1000 – 1800	$1.26\times10^{-3} - 2.26\times10^{-3}$		
Martensitic stainless steel (annealed)	750 – 950	$9.42\times10^{-4} - 1.19\times10^{-3}$		
Ferrite (manganese zinc)	350 – 20 000	$4.4\times10^{-4} - 2.51\times10^{-2}$	At 0.25 mT	Approx. 100 Hz – 4 M
Ferrite (nickel zinc)	10 – 2300	$1.26\times10^{-5} - 2.89\times10^{-3}$	At ≤ 0.25 mT	Approx. 1 kHz – 400
Ferrite (magnesium manganese zinc)	350 – 500	$4.4\times10^{-4} - 6.28\times10^{-4}$	At 0.25 mT	
Ferrite (cobalt nickel zinc)	40 – 125	$5.03\times10^{-5} - 1.57\times10^{-4}$	At 0.001 T	Approx. 2 MHz – 150
Nickel iron powder compound	14 – 160	$1.76\times10^{-5} - 2.01\times10^{-4}$	At 0.001 T	Approx. 50 Hz – 2 M
Iron powder compound	14 – 100	$1.76\times10^{-5} - 1.26\times10^{-4}$	At 0.001 T	Approx. 50 Hz – 220
Silicon iron powder compound	19 – 90	$2.39\times10^{-5} - 1.13\times10^{-4}$		Approx. 50 Hz – 40 M
Carbon steel	100	1.26×10^{-4}	At 0.002 T	
Nickel	100 – 600	$1.26\times10^{-4} - 7.54\times10^{-4}$	At 0.002 T	
Martensitic stainless steel (hardened)	40 – 95	$5.0\times10^{-5} - 1.2\times10^{-4}$		
Austenitic stainless steel	1.003 – 1.05	$1.260\times10^{-6} - 8.8\times10^{-6}$		
NdFeB magnet	1.05	1.32×10^{-6}		
Platinum	1.000265	1.256970×10^{-6}		
Aluminum	1.000022	1.256665×10^{-6}		
Air	1.00000037	1.25663753×10^{-6}		

Nonlinearity and saturation

It is worth noting that high relative permeability material cores do not suit all applications. In fact, the strongest electromagnets, like superconducting electromagnets and pulsed electromagnets, with very high electric current do not use iron cores. For example, magnetization coils used to magnetize Rare-Earth permanent magnets or silicon wafer initialization pulsed magnets.

Responsible for this is nonlinearity of ferromagnetic/ferrimagnetic material's magnetic property. Below shown is annealed pure iron's B-H curve with prominent nonlinearity. In the below graph, the flux density changes linearly with the increase of applied current, in the “linear region”. The increase slows down approaching the “knee” region. Finally, the flux density demonstrates diminishing return in the “saturation” region with the increase of the magnetic field strength. This saturation point creates a cap for the magnetic field strength. If the intended operating point is higher than the saturation point, the nonlinear core material is not suitable for the application. Air, on the other hand, has unity relative permeability; it is a linear medium. At low magnetic field strength, the relative permeability of air is much lower than ferromagnetic metals. However, as magnetic field strength increases, the ferromagnetic media quickly saturate, and their relative permeability dwindle to below unity. At that point, air can deliver more flux than ferromagnetic material. That makes air the choice for superconducting or pulsed electromagnets.

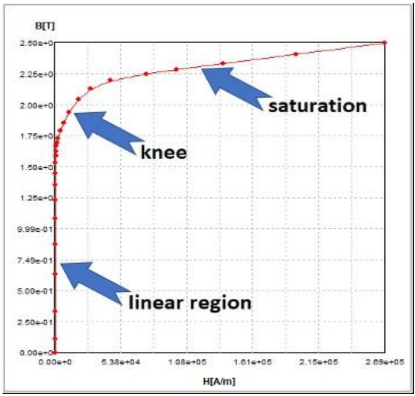


Fig. 1 Soft magnetic material nonlinearity

Residual Field and Mitigation

"Air core" electromagnets lose all magnetism when the electric current is shut off . This is not the case for electromagnets with metal cores. This phenomenon is called hysteresis.

Magnetically "soft" material has small regions called magnetic domains. They act like tiny permanent magnets. Before electric current is applied to the electromagnet coil, the tiny magnetic domains in the core material point to random directions and the magnetic dipole moments cancel out each other as a whole. As a net result, the core material exhibits magnetic neutrality, and the magnetic field in the air gap is zero.

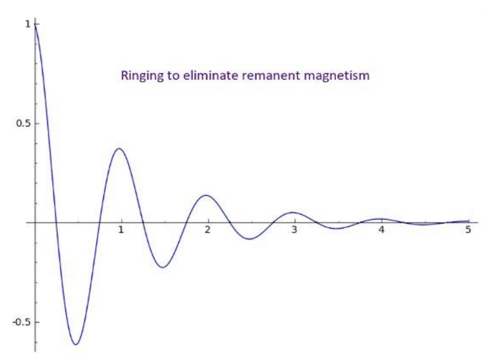
When a current is passed through the coil, it generates a directional magnetic field inside the core, which aligns some or all the core’s magnetic domains. These aligned domains create a magnetic field of their own and add to the magnetic field generated by the applied current. The higher the applied current, the stronger the magnetic field in the core and air gap. When the current is reduced, the aligning field decreases, some magnetic domains return to random state, and the overall field in the core and air gap decreases accordingly.

When the current is completely shut off, however, some of the alignment persists because a few of the domains have difficulty turning their direction of magnetization. A nonzero field remains in the core and air gap ;this remaining magnetic field is called remnant magnetism and the phenomenon is called hysteresis.

The residual magnetic field is not desired in certain applications. For example, the residual magnetism in lifting electromagnets can reduce productivity or even become a safety issue. Two approaches are explained below to eliminate residual magnetic field in electromagnets; “ringing” and magnetic annealing.

Ringing

The most recognized approach to eliminate residual field is “ringing”; or the application of sinusoidally decaying current to the electromagnet coil instead of simply reducing the current to zero. Many power supplies for electromagnets have this feature built in these days, or a handy user can build his own harmonic LC oscillating circuit to achieve the purpose.



Magnetic Annealing

The other approach is magnetic annealing. It is a heat treatment process consisting recrystallization of soft magnetic material and removal of any trace of work hardening. Hydrogen is the best atmosphere for magnetic annealing[4], being it a highly "reducing" gas by reducing the oxides on the part surface and promoting a clean surface finish. The control of the soak temperature, soak time, cooling rate and furnace atmosphere is essential to reach the optimum soft magnetic properties.

Typical soft magnetic material that requires magnetic annealing include Carpenter 49, HYMU 80, Mu-Metal, 4750 nickel iron and Hiperco 50. Even carbon steel can benefit from magnetic annealing if the conditions are right. Key benefits of magnetic annealing include[5]:

- High saturation magnetization
- High permeability
- Low coercive force
- Small hysteresis loop which leads to minimized energy loss.

Lower coercive force and smaller hysteresis loop lead directly to lower remnant magnetism. In turn, this provides a consistently applied magnetic field for every use. Ringing and magnetic annealing can be used in combination for the best residual field reduction.

Material manufacturers usually have standard heat treatment process specified to achieve optimal magnetic properties. For example, for Hiperco 50A the standard heat treatment process is, anneal parts at 1575/1600°F (857/871°C) for 4 hours in dry hydrogen or vacuum and cool at 250/400°F (139/222°C) per hour until 600°F (316°C) is reached, after which any cooling rate can be employed. Your local heat treater often has the standards on file.

Field Requirements Uniform Field

It is commonplace that applications call for uniform magnetic field. A uniform magnetic field usually means the amplitude and vector direction of the magnetic flux density are nearly the same across a volume of interest. In practice, a magnetic design engineer examines the distribution range of the main field components – Bx, By, or, Bz in Cartesian coordinate system – in the volume of interest to assess field uniformity. In a simplified electromagnet as shown in Fig. 2, the volume of interest is the air gap noted. A narrower B range indicates a more uniform field. The magnetic design engineer completes the uniformity assessment by also examining the magnetic flux line directions throughout the volume of interest for signs of fringing ("bulging out") effect.

There are a few ways to achieve uniform field designs. Unitizing pole pieces is one of them. Pole pieces are ferromagnetic or ferrimagnetic material – soft iron being the most frequently used – of high permeability placed immediately next to the volume of field interest. High permeability directly translates into low magnetic reluctance. This allows magnetic flux lines to shift, redirect, or redistribute with much less efforts – consumption of magnetic motive force – than in air. This results in equally spaced flux lines – more uniform field. Also, due to the steep contrast of permeability difference, when magnetic flux lines leave the pole pieces and enter the air gap, they do so with a near 90° entry angle. The pole pieces create uniform flux density and same direction flux lines, as an example shown in Fig. 2.In the yoke region “A” the flux lines are packed much denser than region “B”, therefore the field distribution in the yoke cross section is extremely non-uniform. The pole piece usually consists of high permeability material; it serves the purpose of redistributing the flux lines, resulting in a much more uniform field in the air gap.

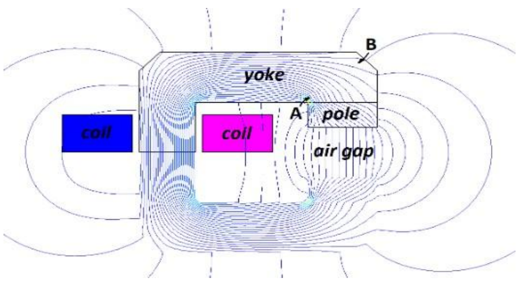
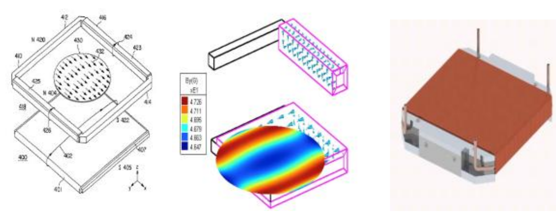


Fig. 2 Magnetic pole pieces and uniform field lines

The center of the air gap usually sees a higher field than toward the ends pole pieces within the air gap. To eliminate this hot spot, an experienced design engineer can increase the reluctance at the center of the pole pieces. To reduce reluctance, the center can be thinner , an air pocket can be added, a part of the pole piece can be substituted with nonmagnetic material (aluminum, for example), or a non-uniform air gap can be used.

Dexter’s patent US6,249,200 B1 introduces a unique magnetic design to achieve uniform field. The design includes a combination of two electromagnets: a plate shaped electromagnet and a frame shaped electromagnet. Each of these two electromagnets generates its own magnetic field. The plate electromagnet design tends to have a higher field region in the center of the volume of interest, while the frame electromagnet design exhibits an opposite field profile which demonstrates a lower field in the center of the volume of interest. Superposed, the resultant net magnetic field within a volume region can be very uniform. The design is shown in the images below, where the arrows in Fig. 3 (a) indicate the magnetic field orientation and demonstrate the degree of uniformity that the flux lines distribute in the volume of interest. An underlining magnetic model of the design is shown in Fig. 3(b), where the magnetic field in a silicon wafer area is shown to have a very narrow range. Fig. 3(c) shows an embodiment of a simplified version of the design for silicon wafer alignment use with water cooling brass tubes integrated.



(a) (b)
(c)

Fig. 3 Patented uniform field electromagnet design

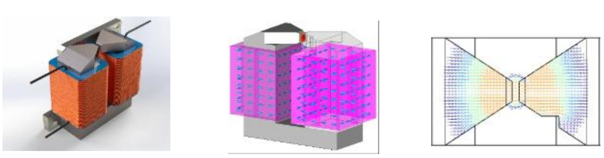
High Field

Emerging applications and end-uses constantly push the limits of electromagnet field strength. From the design engineer’s perspective, the factors that have direct impact on increasing magnetic field include higher current in the coil winding, lower magnetic reluctance in the magnetic circuit, optimized geometry design, and higher efficiency. Without restating common knowledge, the following sections focus on only a few of the key design considerations that promote the magnetic field in the working air gap.

a. Pole shaping

High magnetic field can be achieved by appropriately shaping the pole piece geometry. Assume the electromagnet circuit is not saturated, then the magnetic flux is completely contained in the core and pole pieces (no leakage field). If the pole tip region becomes narrower, the magnetic flux lines would have to be more closely packed when they travel past the pole tips; therefore, the flux density B in the pole tips as well as the air gap would become higher (assuming limited degree of fringing). Fig. 4(a) shows an HDD read/write head setting electromagnet featuring 1.8T high field with tapering poles and automatic thermal

shutoff. Fig. 4(b) details the electric current flow directions and the high field region in the air gap. Fig. 4(c) further demonstrates the flux density B – represented by colored arrows – follow the geometry profile of the tapering poles and its field increases as it approaches the air gap. It is an efficient design if the B operating point in the air gap is just at or slightly above the saturation of the pole material.



(a) (b) (c)

Fig. 4 High field electromagnet design

a. Adjustable pole

Due to the relatively low permeability compared to that of the core material, the magnetic reluctance of the air gap can be dominant in the magnetic circuit. It is well known that the gap reluctance is proportional to the gap distance g, therefore adjusting g is the most effective way to increase field strength. In the example given in the below image Fig. 5, the poles of the electromagnet are independently adjustable to change the air gap. The customer reaps the benefit to adjust the gap distance and field strength to be versatile to fit the varying needs of their applications.

Fig. 5 Adjustable pole electromagnet

b. Pulse electromagnet

One way to increase electric current in an electromagnet is through pulsed designs. The electric energy is built up in a capacitive bank and pulsed/discharged into an aircored coil for a very short duration. The pulse width is typically just a few milliseconds and both the pulse amplitude and width depend on the circuitry parameters such as the capacitance of the capacitor bank, the inductance of the coil, and the total resistance of the electric circuit. The field amplitude also depends on the nonlinearity of the core material magnetic property (for iron-cored coils). As described earlier, soft iron (or other soft magnetic material) has high initial permeability which helps concentrate the magnetic flux lines, but the permeability drops rapidly as current increases to saturate the core, resulting a limited magnetic field.

Added drawbacks of using magnetic cores in pulsed electromagnets are eddy current loss,hysteresis loss, and structural instability due to huge mechanical force during the leading and the trailing of the pulse. As such, most pulse electromagnets use coreless (air-core) designs. While the magnetic cores typically saturate around 2.0 – 2.4 T range, the coreless electromagnets can easily reach into the 6 – 7 T range. Examples of pulse electromagnets are magnetizing coils (Fig. 6(a), with cooling water inlet and outlet) and silicon wafer initializer electromagnet (Fig. 6(b)).

(a) (b)

Fig. 6 Pulsed Electromagnets

c. Pulse electromagnet

Due to the relatively low permeability compared to that of the core material, the magnetic reluctance of the air gap can be dominant in the magnetic circuit. It is well known that the gap reluctance is proportional to the gap distance g, therefore adjusting g is the most effective way to increase field strength. In the example given in the below image Fig. 5, the poles of the electromagnet are independently adjustable to change the air gap. The customer reaps the benefit to adjust the gap distance and field strength to be versatile to fit the varying needs of their applications.

Efficiency

A good electromagnet design is one of high efficiency. The benefits of efficient magnetic designs are multifaceted: a mild rather than severe temperature rise of the coil, gentle cooling schemes, less magnetic field leakage (that might harm the normal operation of sensitive apparatus), lower power consumption, and more compact designs (to save real estate). These are just a few examples of efficient magnet design options. We will examine magnetic design efficiency from the below points of view.

a. Linear region operation

Components of an electromagnet, cores, yokes, pole pieces, etc., are often made of material with nonlinear magnetic properties. Most common such material are pure iron, carbon steels, mu-metal, Hiperco 50A, Vacoflux 50, and alike. The B-H curve of such materials have a quasilinear region where the magnetic flux density changes near linearly with magnetic field strength. This is an operating region before saturation is reached in these components. The material can accommodate even more flux lines before it has to push flux lines out into surrounding air, so at that point the leakage field is very low. Nearly all the input power is used to generate magnetic field in the air gap. A design engineer should target an operating point in the upper linear region just about to enter saturation.

b. Minimizing magnetic reluctance

It should be the design engineer's goal to minimize magnetic reluctance in the component parts in the magnetic circuit surrounding the working air gap, while maintaining reasonable balance between performance and economics. From Eq. (2) we already know that the magnetic reluctance is expressed as,

$$R = \frac{F}{\Phi} = \frac{l}{\mu_0 \mu_r S}$$

(Equation 3)

where F is magnetomotive force. It becomes clear from Eq. (3) that it helps to reduce reluctance by shrinking circuitry component lengths, increasing cross section area, and using material of high relative permeability while balancing performance and cost.

c. Minimizing Loss

Loss comes in the forms of copper loss and iron loss. Copper loss is the resistive loss happening in the current conducting wires. Optimized selection of wire gauge helps to reduce copper loss. When selecting the wire gauge, the design engineer should also take into account the maximum current load (ampacity) and the duty cycle of operation of the electromagnet. Iron loss includes hysteresis loss and eddy current loss; these apply to AC and pulsed electromagnets. Hysteresis loss is less for component material with narrower hysteresis loop. For applications with prominent eddy current loss, laminations should be considered when designing the electromagnet.

d. Uniform distribution of magnetic flux

The overall magnetic reluctance is not low enough unless every section of the magnetic circuit operates either in the linear region or just about to enter saturation. It takes just one section to operate in heavy saturation to bring down the efficiency of the entire magnetic circuit. This can be thought as a “choking point”. Detection of “choking points” involves analysis of flux density or permeability distribution in the magnetic components to identify hot spots – the flux density should not be too much higher than Bs (saturation flux density), and the permeability should not be too low. The usual suspects of saturated magnetic components include magnet backirons (especially if the magnetic flux lines have to make a sudden turn in the backirons), a converging point of multiple paths, any sharp corners, and any parts with a sudden narrowing of the cross section.

e. Pulse width and amplitude

The magnetic field amplitude and pulse width are two key characteristics for pulsed electromagnets, and are directly related to the energy consumption. A design engineer should wisely choose the safety margin so that the solution is not overengineered, leading to other inefficiencies. A pulsed electromagnet connected to a capacitor bank as the power source can be simplified as an RLC series circuit. Therefore, when the capacitor is discharged, the current response can be an underdamped, critically damped, or overdamped response, as shown in Fig. 7. The R, L, C parameters can either be calculated or extracted from the power supply datasheet. Equipped with the right parameters, the damping factor, time constant, pulse width and amplitude can all be calculated. It is not the scope of this work to detail the calculation of these characteristics.

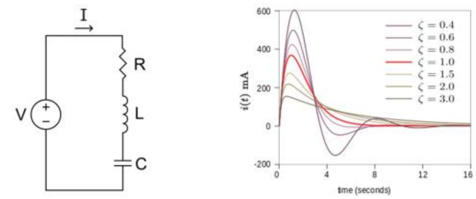


Fig. 7 High field electromagnet design

Safety Considerations

Common safety considerations from any kind of engineering design work can be included in designing electromagnets. There are some additional unique aspects of designing electromagnets, some of which are outlined in the below discussions, and should be considered.

Coil potting. Pulsed electromagnets are subject to substantial mechanical impacts and structural strains. The coil is usually potted to protect it from fatigue and premature failure. If not potted in place, the coil would experience cyclic movements which lead to insulation compromise or abrupt force load on adjacent components which is the reason for vibrations, acoustic noises, and even structural failure.

Thermoswitches. These devices can be applicable to any type of electromagnets. If the coil is allowed to continuously operate, the temperature of the wires keeps rising until it reaches an equilibrium. The center of the coil has a higher temperature than the surface because of unideal heat exchange conditions. At some point the enamel insulation layer will melt and cause a short circuit. To prevent this from happening, thermoswitches can be attached to the surface or interior of the coil to cut off current flow and give the electromagnet time to cool off to an acceptable temperature before operating again.

Cooling. Cooling is necessary to deal with temperature rise within the coil windings to prevent electrical insulation failure or system meltdown. Most common are pressured air cooling and unpressured pressured water cooling. It is achieved by cooling channels designed inside the electromagnet that surround the coil wires and allow cooling mediums to flow through and take away heat. Hollowed magnet wires are also anther method used to allow cooling water to flow through and remove heat from the coils. Grounding. Grounding should be designed into medium to high voltage application electromagnets. Grounding protects operation personnel and against undesired electrostatic discharge (ESD). The electromagnet should share the same electrical ground as the power supply.

Hi-Pot test. The Hi-Pot test is conducted for high voltage or pulsed electromagnets to ensure the adjacent wires of the coil have good insulation to prevent a shorted circuit.

Summary

Several aspects of designing electromagnets are presented in this article, intended to be a reference for design engineers. The key topics covered include common soft magnetic core material, nonlinearity and magnetic saturation, residual field mitigation, uniform field and high field designs, achieving efficient electromagnet designs and safety considerations. This is by no means the exhaustive list of the electromagnet design key elements, since every application is different. Rather, it is the author’s hope that this article can provoke some thoughts on electromagnet designing and inspire creativity among fellow design engineers.

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