Magnetic Shielding

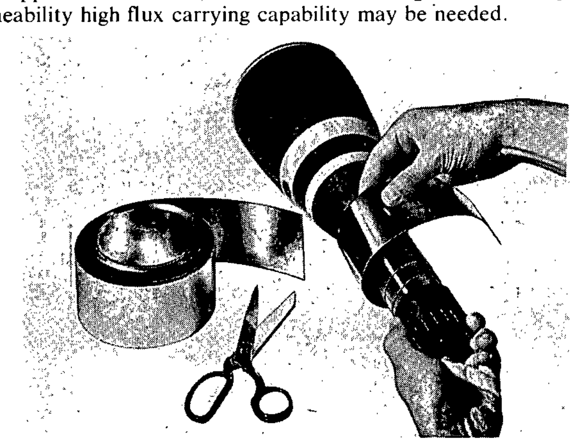
The Need for Magnetic Shielding.

Without magnetic shielding much of today's sophisticated electronic gear would be larger, less efficient and in some magnetic environments, impossible to function at all. As components are made more sensitive and packaging more dense, susceptibility to electromagnetic interaction increases dramatically even in the best engineered layouts.

Magnetic interference with proper functioning can originate from various sources. These could include permanent magnets or electromagnets, coil components such as transformers, solenoids and reactors, AC or DC motors and generators, and cables carrying large DC or AC current at power frequencies. In many cases, even the normal earth's magnetic field can affect proper functioning.

To assure optimum performance, stray magnetic fields must be directed around critical electronic components as a rock in a river diverts running water. This is accomplished by a magnetic shield of high permeability (indicative of the ability of a material to carry a flux) which provides a low reluctance path guiding the magnetic flux around the critical area. Field intensities encountered will usually be under 10 oersteds, and field frequencies from DC to 800 Hertz although shielding alloys are effective at much higher frequencies.

Shielding is accomplished by placing a material with a permeability much greater than one between the field source and the sensitive components affected. Such material must be conductive to prevent passage of electric fields and highly permeable to prevent passage of magnetic fields. Shielding materials commonly used have permeabilities from 300 to over 500,000 depending on flux density. Magnetic shield effectiveness is directly proportional to shield thickness because the shield's reluctance to magnetic flux is inversely proportional to its thickness. It is essential to minimize joints or air gaps which can reduce shielding effectiveness not only by enabling magnetic interference to leak through but significantly affecting the path's reluctance, resulting in a lower effective permeability. The degree of shielding achieved by a given total thickness of material can be increased by dividing it into two or more concentric shields separated by at least the thickness of the material. In such case, a medium permeability material should be used for one layer and a high permeability material for the other layer. The lower permeability material should be located closest to the field source. Thus the medium permeability laminae acts as a buffer and sufficiently diverts the magnetic field to enable the lower reluctance (higher permeability) material to attain the required attenuation. When the external field is strong enough to cause the medium permeability material to approach saturation, an additional diverting shield of low permeability high flux carrying capability may be needed.



Time Saving, Convenient Foil is easily cut with ordinary scissors into magnetic shields, solving many shielding problems. After cutting, foil is quickly hand trimmed to the correct outline and fitted around the component to be shielded. Simple trial and error determines whether one, two, or more layers are needed to achieve the desired attenuation. Ideal for experimental applications or where relatively few shields are needed. Especially practical for hard-to-get-at places, and for making assemblies more compact by placing magnetically reacting components closer together without performance degradation.

TERMINOLOGY, IN ORDER OF USE, WITH SI UNIT AND SYMBOL

ϕ = Magnetic flux (weber, Wb)
B = Magnetic flux density (tesla, T)
$\mathfrak{R}$ = Reluctance
$\mathfrak{F}$ = Magnetomotive force
H = Magnetizing force (inducing magnetic force field)
μ = Permeability (B/H)
μ_o = Permeability of free space (vacuum)
μ_r = Relative permeability, μ/μ_o
L = Coefficient of self-inductance (inductance, henry, H)
E = Induced voltage (volt, V)
I = Current (ampere, A)
J = Intensity of magnetization
x = Magnetic susceptibility
N = Number of turns
r = Radius

BASIC MAGNETIC RELATIONS

$F = k\ mm'/r^2$	Force between magnetic poles m, m'
$MMF = \phi\mathfrak{R}$	Magnetic Ohm's Law
$MMF = NI$	Magnetomotive Force
$B = \mu H = H + 4\pi J = \mu_o (H + J)$ $= \mu_o (1 + x) H$	Flux Density, by definition
$E_L = -N\ d\phi/dt$	Induced EMF in N turns
$E = BLv$	Induced EMF in straight wire length L, velocuity v, in field B
$E = -L\ dI/dt$	Coefficient of self-inductance (inductance L), by definition
$x = J/H$	Magnetic Susceptibility, by definition
$\mu_r = \mu/\mu_o$	Relative Permeability, by definition
$L = N\phi/I$	Inductance of coil of N turns

FLUX AND FLUX DENSITY

	CGS UNIT	MKS UNIT	RELATIONS
FLUX (ϕ)	line (maxwell)	weber	1 weber = 10^8 lines
FLUX DENSITY (B)	gauss* (1 line/cm^2)	tesla (weber/m^2)	1 tesla = 10^4 gausses

*Terrestrial magnetic fields often are described in units of gammas (1 gamma = 10^{-5} gauss = 10^{-9} telsa)

MAGNETIC FORCES—MMF AND H

	CGS UNIT	MKS UNIT	RELATIONS
Magnetomotive Force (MMF,$\mathfrak{F}$)	gilbert (dyne/unit pole)	ampere-turn	1 gilbert = $10/4\pi$, or 0.796 ampere-turn
Magnetizing Force Field (magnetizing field, H)	oersted (gilbert/cm)	ampere-turn/meter	1 oersted = $10^3/4\pi$ or 79.577 ampere-turn/meter

FLUX DENSITY

SYMBOL	DEFINITION	MKS UNIT	CGS UNIT	RELATION
B	Flux density resulting from magnetizing force field H. $B = \mu H$ $\phi = \iint BdA$ (flux = B $\times$ Area)	tesla, T (weber/m^2)	gauss (1 line/cm^2)	1 tesla = 10^4 gausses

RELUCTANCE AND PERMEABILITY

SYMBOL	CGS UNIT	MKS UNIT	RELATION
Reluctance, $\mathfrak{R}$	$\frac{\text{gilbert}}{\text{maxwell}}$	$\frac{\text{ampere-turn}}{\text{weber}}$	Magnetic resistance ($\mathfrak{R} = \mathfrak{F}/\phi$); "magnetic ohm"
Permeability, μ	gauss/oersted	$\frac{\text{weber}}{m^2} / \frac{\text{amp-turns}}{m} = \frac{\text{weber}}{\text{m-amp-turns}}$	Reciprocal of reluctivity; B/H; $\mu_r = \mu/\mu_o$; $\mu_r = 1 + x$
Permeance $\mathcal{P}$			Reciprocal of reluctance
Reluctivity ν			Reluctance/unit volume; reciprocal of permeability

Many magnetic shielding problems can be solved with a pair of scissors and a sheet of magnetic foil. The thickness of the shield and the number of layers required are determined first by simple formulas. The foil is then hand-trimmed to the required outline and fitted around the structure to be shielded. Measurements then tell whether refinements are needed. If you have only a few shields to worry about, the job is done. If you have thousands to make, this is still a good initial design procedure.

Satisfactory ductile foil material ranging from 0.002 to 0.01-in. thick, is available in a variety of permeabilities. It may be best to start with 0.004 or 0.006-in. thickness. Adhesive tape can hold the shield in place. Low-permeability foils are usually 0.004-in. thick, and high-permeability foils can be obtained as thin as 0.002 in. Several widths are available.

Mathematical approach

The best materials to use, the most efficient geometries and the degree of shielding attainable can be found out by trial and error, but that's time-consuming and imprecise. On the other hand, a purely mathematical approach can be very complex, and because of the many simplifications and assumptions that must be generally made to simplify calculations, the results can be unreliable unless the engineer makes some measurements. An approach that combines the insights of a mathematical analysis and practical trial and error, produces the best results.

The mathematical analysis of magnetic shielding is an ancient subject.[1] One of the first conclusions drawn by investigators was that multiple, concentric shields are more effective than increased thicknesses of a single magnetic material shell. Beyond a certain thickness, it has been found, much greater shielding can be obtained if the shell is divided into several layers of alternate magnetic and nonmagnetic material. For a sphere or long cylinder, when the radii of the layers are large compared with their thickness, best results are obtained when the alternate magnetic-nonmagnetic layers are approximately equally thick.

The general equations for calculating the degree of shielding in multilayer shells are complex; a calculator or computer is usually required to obtain solutions. But for a single-layer enclosure, an approximate solution is:

$$g_1 = H_0/H_i = \frac{\text{field intensity outside the shield}}{\text{field intensity inside the shield}}$$

$$\begin{aligned} &= (\mu/4)\,(1 - r_i^2/r_0^2) \\ &= (\mu/4)\,[(t^2/r_0^2) - (2t/r_0)] \\ &\cong \mu t/2r_0 \;(t \ll r_0), \text{ when } (r_0 - t) \text{ is substituted for } r_i. \end{aligned} \qquad (1)$$

where,

μ = permeability of the magnetic material,
r_i = inner radius of the shield,
r_o = outer radius of the shield,
t = thickness of magnetic material.

These equations are valid for spherical shields or for cylindrical when the length-to-diameter ratio is 4 or more. For multilayer shields, each additional magnetic-material layer around the first layer multiplies the attenuation by roughly

$$g_{ij} = \mu t^2/r_0^2 \qquad (2)$$

As an example, assume that a shield is in the form of a long cylinder with an OD of 2 in. and wall thickness of 0.02 in. and that the shield material has $\mu = 10^5$. Then the shield can produce attenuation of $0.02 \times 10^5/2 \times 1 = 1000$. Doubling the thickness of the material would only double the attenuation. But if a second 0.02-in.-thick magnetic layer, about 0.02-in. away, surrounds the first, the attenuation is 40 times greater, or 40,000. The space between the two magnetic layers must be occupied by nonmagnetic material, such as copper, aluminum or any dielectric material.

Magnetic saturation

Equations 1 and 2 are approximations; but, even with use of a fully expanded equation,[2] the results are still approximate. This is because all mathematical analyses assume that the magnetic material behaves linearly—flux density is directly proportional to magnetomotive force—and that, thus, μ is a constant. This is not true, especially with the high-permeability materials that are used for shielding. In addition to nonlinearity, magnetic materials saturate. At saturation the permeability is very low, and the material has little shielding ability.

Experience indicates, therefore, that the thickness of shield material should be selected to keep the flux density in the material in the range of 2500 to 3500 gauss, because generally the permeability is maximum in this region of flux density. When the flux densities become larger than can be handled by a single sheet of foil material, multiple layers can be used. Or heavier-gauge sheets, to about 0.05 in., can be bent, stamped or drawn into the desired shape with shop tools. However, unlike foil, heavier-gauge material requires heat treatments after fabrication.

Obviously, it is desirable to use shield material with the highest possible μ. However, as the magnetic material table shows, high-permeability materials saturate at lower flux levels. Thus when multiple-layer shields are designed to provide high levels of attenuation, the outer layer (which is exposed to the highest intensity of flux density) should be selected from high-saturation-level, albeit lower-μ, material. Shielding materials are classed as having low, medium or high permeability. Low-permeability materials, though, have high saturation levels—18,000 to 20,000 gauss. Medium-permeability materials saturate at somewhat lower levels—roughly 15,000 G. And the high-permeability materials saturate in the 7500-to-9000-G. range. Also, retentivity is related to permeability. Minimum retentivity may be an important requirement for assemblies that are sensitive to low dc magnetic fields. High-permeability materials have the lowest retentivities.

An example where theory can be misleading because of saturation occurs in the often-quoted criterion[2] for optimum shield thickness.

$$t = 3r_i/2\mu$$

In this case it is better to use multilayered construction. In the previous example, with $r_i \simeq 1$ in. and $\mu = 10^5$, $t = 1.5 \times 10^{-5}$ in. However, most magnetic materials, when this thin, quickly saturate in a field of any reasonable intensity. Moreover the material would be too fragile to fabricate.

The need for magnetic shielding

It is often hard to determine whether a problem is caused by magnetic fields. Many sources, including the earth, generate magnetic fields. Other system components, such as CRTs, photomultipliers, every coil and magnetic memories and tapes, can be affected by these fields. The effect can be a simple positioning error in a dc field. If the field is time-varying, it can cause hum or degradation of a CRT's resolution.

It used to be difficult to measure a magnetic field accurately. A small coil, excited with a distinctive ac signal, could serve as a source to determine if the circuit was susceptible to magnetic interference. The small coil could also be used as a pickup probe to detect ac fields. Though crude, these improvisations were often very effective, but they provided little in the way of accurate measurement of the field strengths that were present. Today, gaussmeters accurately cover the range from 0.02 to 50,000 G for frequencies from dc to 20 kHz and higher, and provide direct readings as easily as a voltmeter. The probes to detect the magnetic field are usually Hall-effect, InAs elements. For calibration, the National Bureau of Standards will certify the flux value of a simple permanent-magnet reference. A well-stocked electronic laboratory should have a gaussmeter, and its probe can be used to hunt and measure interfering magnetic fields with ease.

BASIC MAGNETIC PARAMETERS

Magnetic Property	**Symbol**	**Defining Equation**	**MKS Unit**	**CGS Unit**
Magnetomotive Force	$\mathcal{F}$	$\mathcal{F} = NI$	ampere-turn	1 gilbert = $10/4\pi$ or 0-79577 ampere turn
Flux	ϕ	EMF = $-Nd\phi/dt$	weber[1]	1 maxwell (line) = 10^{-8} weber (1 weber = 10^{8} maxwells)
Reluctance (Magnetic Resistance)	$\mathfrak{R}$	$= \frac{\mathcal{F}}{\phi}$	$\frac{\text{ampere-turn}}{\text{weber}}$	$\frac{\text{gilbert}}{\text{maxwell}}$ = magnetic ohm
Reluctivity	ν	Reluctance/unit length		
Magnetizing Field (inducing magnetic field)	H	$H = d\mathcal{F}/dl$	$\frac{\text{ampere-turn}}{\text{meter}}$	1 oersted = $10^{3}/4\pi$ or 79.577 amp-turn/m
Flux Density (resulting induced magnetic Induction Field)	B	$B = \mu H$ $\phi = \iint B\,dA$ (Flux = B $\times$ Area)	tesla = weber/m² $= \frac{\text{newton}}{\text{amp-m}}$	gauss = 10^{-4} tesla (1 tesla = 10^{4} gausses)
Permeability	μ	$\mu = B/H$; inverse of reluctivity	$\frac{\text{weber}}{\text{m}^2} \Big/ \frac{\text{amp-turns}}{\text{m}}$ $= \frac{\text{weber}}{\text{m-apere-turns}}$	$\frac{\text{gauss}}{\text{oersted}}$
Permeance	$\mathcal{P}$	Inverse of reluctance		
Inductance	L		henry = inductance that produces counter-EMF of 1V when current changes at a rate of 1 amp/second	
Intensity of Magnetization	J	$B = \mu_0 (H_0 + J)$; $J = xH$	amp-turn/meter	oersted
Susceptibility	x	J/H	dimensionless	dimensionless

[1]Weber = Joule/amp = volt-sec
[2]Permeability of free space (μ_0) = $4\pi \times 10^{-7} \frac{\text{Joule}}{\text{amp}^2\text{-meter}} = 4\pi \times 10^{-7} \frac{\text{weber}}{\text{amp-meter}} = 4\pi \times 10^{-7} \frac{\text{henry}}{\text{meter}}$

After the offending field is detected and mapped, the accessibility and component layout in the region of the field will determine whether it is better to enclose the source or the pick-up device, or perhaps both. A first-trial shield can be put together with the foil-and-scissors technique, and the results can be checked with a gaussmeter probe. Several adjacent foil layers can be applied to provide a simple, thick shield. Or a spirally wound foil, sandwiched with copper or aluminum foil, can produce a multilayer shield for greater shielding.

When the shape, thickness, number of layers and material types have been established by rough mathematics and measurements, more permanent designs can be undertaken, and companies that specialize in magnetic-shield fabrications can be called in. Now you can talk intelligently, with known facts and figures. Often a manufacturer may have a stock shield to suit your problem, or he may be able to modify one of his shields economically.

Electrostatics

Since ferromagnetic shielding alloys are reasonably conductive, proper grounding of an electromagnetic shield can usually provide an adequate electric-field shield at low frequencies. Grounding is not necessary to obtain magnetic shielding, but it's good practice. At increased frequencies, skin effect becomes a dominant factor, and the conductivity of the shield material should be greater than that of permeable alloys. For good conductivity, materials like aluminum or copper are needed. One way of combining magnetic and electrostatic capabilities in a single-layer shield is to copperplate the magnetic shield with sufficient copper to satisfy skin-effect requirements.

References

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