FACTORS IN EMI ATTENUATION

An understanding of EMI attenuation factors enables design engineers to choose optimum shielding materials.

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INTRODUCTION

Along the very wide band of EMI, shielding methods change and require different materials. This article explains why and looks at the properties of materials which will best satisfy the requirements for EMI shielding. The influence of different factors on EMI shielding properties will be discussed so that the reader will be able to select the optimum material for the EMI shielding need.

The best way to achieve electromagnetic compatibility is to produce no interference! This is not always possible; but reducing the level of interference in every possible way must be a priority. The next approach to producing EMI-free space is by conducting magnetic lines of interference around the space. Finally, EMI-free space may result by allowing the interference to enter or escape. This means it must be reflected or absorbed. The implementation of these approaches will depend on many factors. This article concentrates on the most important of them, the DiParetto principle.

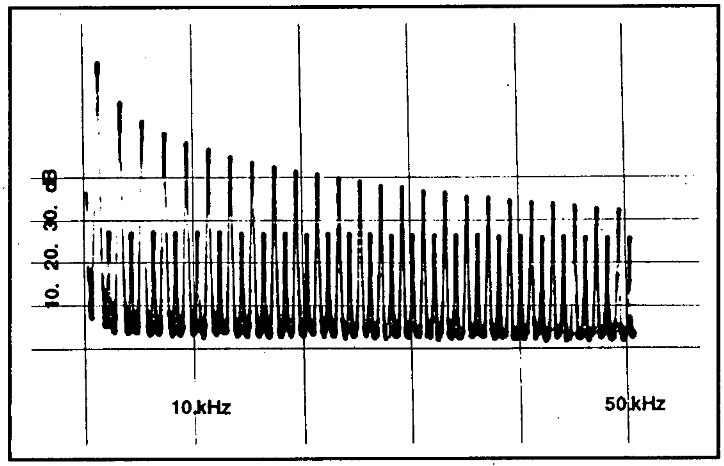

Figure 1. 1.0 kHz Square Wave Displayed on the Screen of Spectrum Analyzer.

EMI ATTENUATION FACTORS

To attenuate EMI, the following factors must be known: frequency spectrum, radiation intensity, interference source, propagation source and attenuation level.

Frequency Spectrum. EMI will seldom affect only a single frequency. In most cases it is a band including fundamental frequency and many harmonics. For the sake of simplicity, most electromagnetic phenomena are discussed in terms of sine waves; in reality, this is rarely true. Figure 1 illustrates a 1.0 kHz square wave as displayed on a spectrum analyzer. It supports the idea that most EMI stretches through the very wide band.

Radiation Intensity. The safest approach is to assume the worst case. Overdesign, rather than underdesign, is recommended.

Interference Source. Is it in the near field region or the far field region? In the far field mode, the EMI signal has an impedance of 377 Ω. Depending on the type of parasitic antenna producing the interference, impedance starts with milliohms for a loop antenna and kilohms for an open dipole in the space next to the transmitting element. At the distance from the antenna of $\lambda/(2\pi)$, where λ is the wavelength in meters (this point will arbitrarily be called the boundary between near and far field), the impedance of the wave approaches 377 Ω. If the interference is introduced as a Thevenin equivalent, it will become obvious that near field interference is harder to control.

Propagation Pattern. Elements may be encountered by a parasitic antenna which will look like directors or reflectors and the pattern of radiation, (initially assumed to have been produced by an antenna with an aperture of less than 1/10λ, by definition) may be changed.

Desired Attenuation. Finally, the desired EMI attenuation level should be known. The best approach for EMI attenuation is to define it in relation to the frequency of the interference. The DC and up to 30 to

Material	Resistivity in $\mu\Omega$ - cm	Depth of Penetration in cm at:		
		100 Hz	1 kHz	10 kHz
Cu (pure)	1.72	.660	.209	.066
Ag (pure)	1.52	.636	.201	.064
Al (pure)	2.87	.839	.265	.084
Zn (pure)	6.10	1.242	.393	.124

Table 1. Depth of Penetration and Resistivity Value for Selected High Electrical Conductivity Materials.

60 Hz region can be considered the starting point. In this age of Mega and Giga, this frequency spectrum looks to be out of focus, but this is the spectrum where the most electrical energy is transmitted and used! Its interference in electromagnetic communications and influence on the performance of other electronic devices cannot be denied. The assertion that low frequency magnetic fields are biologically harmless may not be correct; mounting evidence contradicts this.

EMI IN DIFFERENT FREQUENCY REGIONS

How can EMI in this region be efficiently shielded? As previously stated, EMI shielding action can be effected by the following means: reflection, absorption and bypass. In order to reflect EMI, a reflector must be producible. An electromagnetic wave reflector is a conductive surface where the electromagnetic wave will induce eddy current, but the d Φ/dt in this frequency region is not large enough to produce any significant eddy current.[1] If absorption of low frequency interference is attempted, the depth of penetration, which is $\Delta = k(\rho/\mu f)^{1/2}$, should be addressed.[2] If the frequency is low, the depth of penetration is large. Considering the wavelength in the given media is $\lambda = 2\pi\Delta$ by definition, and the fact that the absorption of the EMI energy occurs in increments of per one wavelength (so as to describe one full hysteresis loop), and numerically is the area $B * H$ in ergs/cm^3, too few incremental steps exist to produce meaningful attenuation at low frequency. A bypass can be constructed. The bypass must have a minimum resistance to the magnetic flux "R_m" - reluctance. The reluctance is a counterpart in magnetic circuit to the resistance in the electrical circuit. So, instead of $R = \rho L/A$, $R_m = 1/\mu * L/A$ can be written.

The flow of magnetic lines is governed by a similar relationship as in electrical circuitry: $I = V/R$, but instead of current, it is the flow of magnetic lines. Instead of voltage, it is a magnetomotive force, and resistance is replaced by reluctance. $\Phi = F\mu(A/L)$ or, the amount of magnetic lines is directly proportional to the μ of the material, available area of the magnetic circuit and the driving magnetomotive force. It is inversely proportional to the length of the magnetic circuit. The last equation defines controlling parameters for the design of an EMI bypass. Should the frequency of the interference be increased, the parameter "A" will be affected.

In the region 60 Hz to 2 kHz, d/dt will be too small to produce sufficiently strong eddy currents. The "bypass" action will be inefficient due to the inability to fully penetrate the shielding material depth of penetration: $\Delta = k(\rho/\mu f)^{1/2}$.[2] So in this new frequency range a magnetic bandpass cannot be produced; it will be too lossy! But reduced depth of penetration shortens the wave length in the media, thus enabling the use of another mechanism for EMI attenuation -- the aborption of EMI energy. The EMI energy loss is controlled by the equation $E = A/4\pi$ per cycle.[3] The mechanisms of absorption are the movement of Block walls, at low field strength, and, at higher levels, the rotation of magnetic domains. Movement of the magnetic field, represented by Block walls, and magnetic domains produce counteraction forces (Lentz's law), thus slowing the speed of movement. Being physical entities, the magnetic domains and Block walls have a moment of inertia. So when the EMI frequency becomes high, these elements just cannot follow the changes in excitation wave $A_t = A_o * \text{Sin}(\omega t)$. Physically, the shielding material becomes "magnetically harder," i.e., its μ value decreases, and the material attenuates less and less.

If copper is alloyed with	The resulting alloy has conductivity in % IACS
Ag (0.27 to 2.0%)	100-101%
P (0.15 - 0.40%)	85%
As (0.15 - 0.50%)	45%
Cd (0.05 - 1.2%)	96 - 90%
Zr (0.10 - 0.20%)	93%
Be (0.7 - 1.9%)	50 - 22%
Cr (up to 1.2%)	80%
Pb (up to 1.5%)	96%
Sn & P (8 and 0.35%)	13%
Zn (5 and up 36%)	56 - 26%
Ni & Co (up to 3%)	45%
Al (5%)	17%
Ni & P (1.38 & 0.35%)	60%

Table 2. Electrical Conductivity.

This leads to the next frequency region, but first, a reminder is appropriate that all magnetic materials can only carry a certain density of magnetic flux. This is defined as $B = \Phi / A$ and is expressed as a number of magnetic lines per unit area. The most popular definition will be Gauss -- one magnetic line per square centimeter. Recently, the standard was set for a Tesla; (T) is equal to 10^4 lines/cm^2. By all means, if conducting high density magnetic currents in the ferromagnetic material is intended, one should know if the given geometry/material combination will carry it.

The next range can be arbitrarily defined as 2 kHz to 50 kHz, and considered a transition region. At the high end of this region the absorption phenomenon will almost cease. But in this range, the $d\Phi/dt$ will be strong enough to produce reflection of EMI very efficiently. What is the mechanism of reflection? The EMI entering electrically conductive material will set up eddy currents in the material. The strength of the eddy field is a function of the induced voltage and the resistance of the material. Surface impedance is what the induced eddy current sees as the resistance of the shielding material.[4] Considering that the surface impedance is the frequency dependent variable, the reflection method of EMI attenuation will work up to a certain frequency range. By varying the conductivity of shielding material, this mechanism can be used up to 0.5 GHz. The higher frequency range of EMI attenuation will be made with such "exotic" means as 377 Ω "space cloth," absorptive cones in certain geometry, etc. One thing should be noted: the higher the frequency of the EMI, the more losses it encounters in any material.

One factor has been omitted: coupling of EM energy to the shielding material. Because this is a highly complicated matter and not well-understood phenomenon, it will be discussed at a later date.

EMI SHIELDING MATERIALS

Table 1 depicts the electrical resistivity of pure metals which have high electrical conductivity. The electrical conductivity is very sensitive to impurities in the metal and alloying processes (Table 2). To a lesser degree the conductivity is sensitive to the condition of the crystalline structure in the electrical conductors (the difference in resistivity between soft and hard drawn copper is 4 percent). Considering that each metal will react to impurities differently, the

Material	ρ	Relative Permeability Min. & Max.	Depth of Penetration in cm at 100 Hz	1.0 kHz	10 kHz
Silver	1.52	1.0	.636	.201	.0636
Copper	1.72	1.0	.660	.2087	.0660
Nickel	8.70	200/600	.0857	.0271	.00857
Aluminum	2.78	1.0	.839	.265	.0839
Zinc	6.10	1.0	1.242	.393	.124
Pure Iron	10.0	150/5.K	.0503	.0159	.00503
3% Si Iron	47	1.5K/40K	.0244	.0077	.00244
4-79 Permalloy	55	20K/100K	.0167	.00528	.00167
Mu-metal	62	20K/100K	.0177	.00560	.00177
49 Permalloy	45	4K/70K	.0180	.00569	.00180
Monel 400	42.5	suppressed Curie Pt.	3.28	1.037	.328
Iron commercial	10.0	80/1500	.0566	.0179	.00566
Invar	80.0	300/1600	.146	.046	.0146
Hyperco-50	26.0	600/6K	.0447	.014	.0045

Depth of penetration $\delta = \sqrt{\rho/\mu f}$ is defined as a plane in the material, where the value of the incoming signal is attenuated to 37% of its value as compared to the strength of the signal at the surface. ρ is resistivity in $\mu\omega - cm$.

Table 3. Resistivity and Permeability Values of Commonly Used EMI Shielding Materials.

most probable candidates are copper and aluminum. The most detrimental additions to copper, in declining order are: additions of P, Fe, B, Si, As, Cr and Bc. The Zn, Au, Cd and Ag have lesser influence, but readers should remember that 1 percent of Bc in copper reduces conductivity to about 45 percent of initial value. Five percent of Zn will reduce conductivity to 56 percent. Similar changes will happen to the other metals also; handbooks should be consulted. The impurities will make metal alloys more sensitive to the thermomechanical treatment. For example, the heavy alloyed aluminum, #7075, will change its conductivity by about 40 percent depending on thermal treatment. The best aluminum material is pure aluminum series #1100, but it is too soft.

The next suggestion would be an alloy of #6000 series with Si and Fe. Again, a look in the handbook will clear many misconceptions.

Two metals deserve a special treatment: iron and nickel. Both are comparatively good electrical conductors (10 and 8.7 $\mu\ \Omega$-cm resistivity respectively), and also have good ferromagnetic properties. Iron is used very extensively in EMI shielding work. The only problem is that most of the product is used in the form of hot rolled plates or sheets. Experiments indicate that annealing of hot rolled products, as available on the market, will increase their shielding performance by 20 to 30 percent (in dB). The #1006 steel is the best commercially available product, although the amount of carbon is already objectionable. The carbon impurity widens the hysteresis loop of iron, making it less effective at low frequencies and low level interference. EMI shielding properties of FE can be improved drastically by the addition of some percentage of Si (up to 3 to 4 percent), or aluminum. Both additions will increase the resistivity of the material, increase the "μ" of it and decrease the width of the hysteresis loop. The nickel is seldom used in sheet form, but Ni plating and Ni loaded polymers are used frequently. Most of the Ni use is in the Ni-Fe binaries, where combinations of Fe with 42 to 80 percent of nickel by weight produce exceptionally soft magnetic materials. Table 3 lists resistivity and permeability data of most commonly used EMI shielding materials. Depth of penetration is also included. Engineers can use the information to calculate the needed thickness of shielding material: considering that one depth of penetration reduces the signal to 37 percent of initial, a generalization can be made that $A_{out} = A_{in}/e^n$; where A_{out} is the voltage out, A_{in} is the voltage of the incoming signal, e = 2.718 and "n" is the number of the depths of penetration. Here 100-percent coupling efficiency can be assumed.

Other materials will work as EMI shielding media in accordance with their value of resistivity and permeability. Zinc, for example, with its low resistivity, will do well. On the other hand, "monel-400" with high resistivity, is not especially good. But in cold weather, where it may become magnetic, the shielding performance will be considerably better. At times, especially in the Gigahertz region, where the depth of penetration is very shallow, conductive material, like brass for example, should be used in microwave guides. Thin film products, like evaporated metal layers on some substrates, or conductive filaments which are later compounded in layers, are also effective at those frequencies. Likewise, polymer mattresses filled with conductive particles are effective at those frequencies, although the performance of such products extends into the lower frequency regions also.

SUMMARY

Important factors to address when attempting to attenuate EMI include the frequency spectrum, radiation intensity, interference source, propagation pattern and desired attenuation levels. Numerous shielding materials and combinations are available. These should be selected based on characteristics such as resistivity and conductivity levels, application forms, necessary thickness levels, environmental conditions and frequency regions. ■

TECHNICAL NOTES

1. The expression $d\Phi/dt$ is the change of magnetic flux with time. This change induces a voltage on the terminals of the open loop equal to: $V = d\Phi/dt$, where V is in volts; Φ is in Webers (10^4 Gauss or lines) and the time is in seconds. This is a statement of Faraday's Law.
2. The depth of penetration, Δ, is defined as the distance from inside the material to the surface of it, where the signal illuminating the surface is attenuated to 37 percent of its nominal value. $A = A_{surface}/e$, where e = 2.718. It can be expressed as: $\Delta = 5030(\rho/\mu f)^{1/2}$ in cm, where ρ is in Ω-cm, f is in Hertz and μ is relative permeability.
3. A is the area under the hysteresis curve inscribed by 2π radians of the wave in gauss times oerstedt. It is very seldom that all available energy of the interference will be coupled with the shielding material.
4. Surface resistance is the resistance value of the bar with equal width and length dimensions and a thickness of one "depth of penetration" as measured along the length axis.