CONCEPTS OF SHIELDING

INTRODUCTION

The following is a discussion on the theory, specifications and some practical aspects of electromagnetic fields and shielding. In substance, it will lead to the conclusion that shielding effectively is a function of the characteristics of the field energy type to be attenuated or reduced.

Shielding is the only practical method of suppressing interference which is radiated directly from a source. A perfect shield will not allow the passage of either electrostatic, inductive or electromagnetic energy.

Aluminum, copper and other low permeability (where permeability is equal to or less than free space permeability of $4\pi x 10^{-7}$ henries per meter) materials when configured as a flat plane will offer good shielding efficiency against high impedance or electric fields. Low permeability shielding materials will not attenuate low impedance magnetic or induction fields unless the shielding configuration is altered to create eddy currents in the low permeability, high conductivity material. The external flux fields of the eddy currents can nearly cancel the impinging magnetic or induction fields, the cancellation or attenuation being determined by the materials' conductivity.

Every source of electric energy is surrounded by a field, a flux field with magnetic lines of force and a potential field. The simple situation of an electric current flowing through a conductor or wire causes a field to exist around the conductor, whose magnitude and direction follow well known principles. Only part of the energy in any field is propagated through space and eventually dampens to zero. This is known as the Fraunhofer zone, or far field.

The remaining part of the energy either returns to its origin (vorticity zone) or is absorbed by some receiving source. A dipole antenna behaves in this manner. Part of its energy becomes a radiation field (at a distance of greater than 3 to 4λ, the field impedance becomes equal to free space impedance of 120π), and the portion which periodically returns to the antenna is the induction/electrostatic or near field.

The general mathematical expression that describes an electromagnetic field is rather complex and is usually discussed in texts on field theory. It is easier to discuss this expression in terms of its electrical vector E and its magnetic vector B, where E has the dimension of V/L and the units of volt/meter and B has the dimensions VT/L2 and the units of volt-seconds/meter. E and B can then be written as the sum of two components.

$$E = E_1 + E_r \qquad \text{Equation 1}$$

$$B = B_1 + B_r \qquad \text{Equation 2}$$

The components of the induction field are:

E_1 and B_1

While the components of the radiation field are given as:

E_r and B_r

E_r and B_r are proportional to Bo/R, where:

$$Bo = \frac{\omega}{v_o} \qquad \text{Equation 3}$$

or

$$\frac{\omega}{v_o} R \qquad \text{Equation 4}$$

Where:

ω is the angular frequency of the field in radians; v_o is the velocity of propogation in meters-per-second; E_1 and B_1 are proportional to $^1/R^2$ where R is the distance from the source in meters. The ratio of the two is BoR or $\omega R/v_o$.

It can be concluded that for very small values of R, and any given values for ω and v_o, the induction field will be very much greater than the radiation field so that in most instances the latter may be neglected. However, if R is very large, the radiation field is important and the induction field can be discarded.

The induction, vorticity or near-zone field is that area immediately around the source volume in and on which charge and current density are non-vanishing, and where BoR is very much smaller than 1 (one).

If this is true,

$$E_1 >> E_r \text{ and } B_1 >> B_r \qquad \text{Equation 5}$$

then:

$$E = E_1 \text{ and } B = B_1 \qquad \text{Equation 6}$$

The equations presented to describe the components of the E_1, B_1, E_r and B_r all contain the term:

$$\epsilon\text{-JBoR}. \qquad \text{Equation 7}$$

Since it has been noted that BoR<<1, then:

$$\epsilon\text{-JBoR} = 1 - \text{JBoR}.$$

This means that almost instantaneous action can be expected at very small distances. Since it has already been established that the induction field is very important at very small distances, it can also be stated that the induction field and an instantaneous acting state are almost identical. The instantaneously acting or stationary state has an electric field component known as the electrostatic field and a magnetic field component known as the magnetostatic field associated with it. Since ω must equal zero in this stationary state, there is no radiation field and only the induction field remains. At near dc and at the low frequencies where ω Rv_o is small, the induction or vorticity field is the entire field.

The low frequencies near (vorticity) and far (Fraunhofer) fields can be defined by:

$\omega = 10^3$ (angular velocity) or 160 hertz;
the near field distance $R \leq 3 \times 10^3$ meters;
the far field distance $R \geq 30 \times 10^6$ meters.

Medium radio frequencies and their near and far fields can be defined by:

$\omega = 10^6$ (angular velocity) or 160 kHz;
the near field distance $R \leq 3$ meters or less than λ;
the far field distance $R \geq 30 \times 10^3$ meters or greater than 3λ.

Induction fields are either high- or low-impedance fields. A high-impedance field is defined as being higher in impedance than that of the dielectric in which it exists; a low-impedance field therefore is defined as being lower in impedance than that of the dielectric in which it exists. High-impedance fields are associated with a voltage source and most of the field's energy is contained in its electric component. Low-impedance fields are associated with a current source and most of the field energy is contained in the magnetic component. Plasma or air as the dielectric is considered to have an impedance of 120π or 376.7 ohms.

In order to contain interference, a good shield should be able to confine undesired signals generated within an enclosure or reduce them to such an extent that no malfunctioning or alteration of performance is noted in nearby equipment. The shield must also prevent susceptible receptors from receiving undesired signals existing in the area. Shielding effectiveness is determined by the following factors:

- The field impinging on the shielding material:
  vorticity zone or near field $R<\lambda$
  Fresenel zone $R+\cong\lambda-3\lambda$
  Fraunhofer zone or far field $R>3\lambda$;
- The impedance of the incident field;
- The intensity of the incident field;
- The frequency of the incident field;
- The tangential angle of the incident field;
- The permeability of the shielding material;
- The conductivity of the shielding material;
- The thickness of the shielding material;
- The surface intrinsic impedance of the shielding material;
- The number of layers comprising a multiple shield;
- The spacing between the layers of a multiple shield;
- The permeability of the dielectric between the layers of a multiple shield;
- The various shielding material combinations or the non-conformity of shield construction;
- The effect of plating or cladding of laminated shields;
- Shielding material configuration; ie: solid, perforated, etc;
- Shielding configuration; ie: box, tube, Faraday Cage, etc;
- The enclosed volume or size of the shield;
- The fixed-seam joint construction; ie: soldered, welded, etc;
- The access-seam joint construction; ie: gaskets, contact fingers etc;
- Trihedral corners;
- Dihedral corners;
- The antenna effect of conductors projecting into a shielded zone;
- Conductive coupling and reactive currents from interference reduction filters;
- Required air-inlet and air-outlet areas;
- Grounding of the shield.

Plane-wave shielding theory is widely accepted for frequencies sufficiently high and distant from the source; frequencies high enough so that induction (magnetic or H field) fields or near-field effects are negligible compared with those of the radiation field. Conventional plane-wave theory is based upon the similarity (in mathematical form) between field equations for the plane-wave case and those for a conventional transmission line.

The analogy between plane-wave and transmission-line theory appears to be lost in the near-field case because the plane-wave equations are no longer similar to those of a transmission line. This disparity can be true if the primary concern is with performance of a shield over an entire wave front. However, whether the entire wave is plane or not is not indicated to the receptor, which is sensitive only to any difference in impedance of the source wave over that of the free-space wave. If this viewpoint is valid, the performance of the shielding material, when measured in the conventional manner, should behave in strict accordance with plane-wave shielding theory.

Several years ago, an experiment was performed at the Research Institute of the Illinois Institute of Technology to verify the validity of this contention. In the study, the various terms of the standard shielding expression.

$$S=A+R+B \qquad \text{Equation 8}$$

were separated on an experimental basis:

A = the penetration loss corresponding to the transmission loss in the transmission line;
R = the reflection loss due to mismatch between the wave impedance in the external medium (air) and the intrinsic surface impedance of the metallic shield;
B = the normally negligible losses, except at the lower frequencies and very thin materials where the penetration loss A is less than 15 dB.

The resulting terms were as predicted by plane wave theory within the accuracy of the experiment.

For the single uniform shield, plane wave shielding theory has been well developed and generally understood. Hence, only the pertinent resulting expressions are presented.

All terms in the shielding effectiveness equations may be expressed as functions of the material conductivity: g; permeability: μ relative to copper or free space; and the frequency f in hertz (cycles-per-second) as the physical relationships that exist.

PENETRATION LOSS

The penetration loss A, depends not only upon μ, f, and g, but also upon the thickness d (in inches) of the shielding material.

$$A = 3.34\sqrt{\mu \, fg \, d} \text{ (dB)} \qquad \text{Equation 9}$$

REFLECTION LOSS

The reflection loss, R depends upon the incident wave impedance Zw ration to the shield's intrinsic impedance.

$$\eta + (1+J)(\pi\mu f/g)^{1/2} \qquad \text{Equation 10}$$

Therefore:

$$R = 20 \operatorname{Log}_{10} \frac{(1+K)^2}{4K} \qquad \text{Equation 11}$$

Where: $K = \frac{Zw}{\eta}$ Equation 12

thus: $R = 20 \, \text{Log}_{10} \frac{K}{4} \, (\text{dB})$ Equation 13

when K is much greater than 1 (almost always true).

CORRECTION TERM FOR INTERNAL REFLECTION

If A is equal to or greater than 15 dB, the correction term, B, may be neglected. The correction term, B, is complex, since it depends on all of the shielding material, dimensional, and frequency parameters.

In the general case,
$B = 20 \, \text{Log}_{10} \, (1\text{-}X10)^{-0.1A} \, (\cos 0.23A) \, \text{-}j \, (\sin 0.23A) \, (\text{dB})$

where: $X = \frac{(1-K)^2}{(1+K)^2}$ Equation 14

In almost all practical cases, X = 1; the only notable exception is the special case of extremely low frequency (ie, less than ≈10 hertz) against low-impedance (chiefly magnetic or H) fields.

For X = 1
$B = 10 \, \text{Log}_{10} \, 1\text{-}2 \, (10^{-0.1A} \cos 0.23A) + (10^{-02A})$
Equation 15

For these extremely low frequencies, where the penetration loss for a single shield is less than 15 dB, multiple shields of N layers will provide greater than 15 dB of shielding effectiveness.

The impedance ratio (K) is always greater for a high-impedance (E) field wave than for a low-impedance (H) field wave. Hence, both the reflection loss and the total shielding effectiveness of a shielding material are always greater for a high-impedance (E) field wave than for the low-impedance (H) field wave. On this basis, high-impedance wave tests never yield a limiting lower boundary on shielding effectiveness and only the low-impedance wave measurement need be performed as a measure of shielding effectiveness.

Corner effects are important considerations for shielding effectively, as shielding effectiveness is at a minimum in trihedral and dihedral corners. A qualitative explanation is as follows.

Current induced in that wall of an enclosure which lies perpendicular to the excitation magnetic field creates its own magnetic flux field in opposition to the original field. However, the induced current does not flow uniformly in lines parallel with the extreme edges of the wall, but in fact, tends to flow across the corner rather than around it. This is similar to the spray-off of radio frequency energy from sharp bends or edges. This tendency to flow across the corner results in a decrease in the opposing magnetic field at this point and a corresponding increase in the penetration of the excitation field. See Figure 1.

INTRINSIC IMPEDANCE

The magnitude of the intrinsic impedance of a metal barrier can be expressed as:

$Zs = (1 + j) \, (\mu fg \, . \, 3.69 \, . \, 10^{-7}) \text{ ohms}$
Equation 16

where:

- μ = relative permeability of the shielding metal relative to free space.
- f = frequency in hertz (cycles-per-second)
- g = the relative conductivity of shielding metal relative to copper.

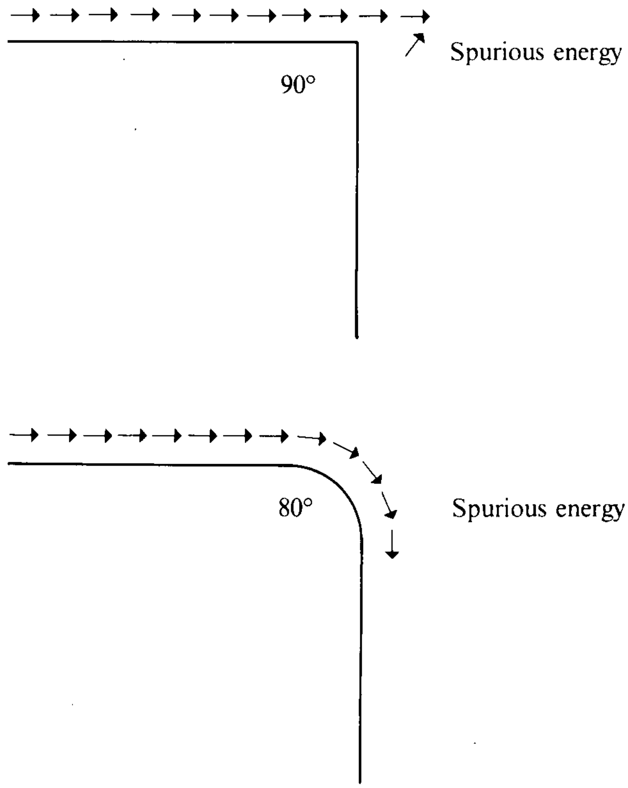

Figure 1. Sprayoff of Spurious Energy.

SHIELDING MATERIAL THICKNESS

The minimum required thickness of the shielding material may be calculated by the following.

$$t = \frac{A}{3.338 \times 10^{3} \sqrt{fg\mu}}$$ Equation 17

where t is the thickness of the shielding metal in mils.

- A = the required absorption-loss in dB
- g = the relative conductivity of the shielding metal relative to copper
- μ = the magnetic permeability of the shielding metal relative to free space
- f = the frequency in hertz (cycles-per-second)

The value of f should be that of the lowest frequency associated with the operation of the equipment being shielded. Use of the lowest frequency is important, since shielding effectiveness is directly proportional to frequency; consequently, attenuation will become greater as frequency increases.

ABSORPTION LOSSES

The absorption losses of a shielding material are a function of thickness and are computed as follows:

$$A = 15.35\, t \sqrt{fg\mu}$$

where A is the absorption loss in dB.

- t = thickness of the shielding metal in mils
- g = the relative conductivity of the shielding metal relative to copper
- μ = the magnetic permeability of the shielding material relative to free space
- f = the frequency in hertz (cycles-per-second).

Table 1 illustrates the shielding parameters for a few types of metals.

CONCLUSION

Thus while the imposed RFI/EMI specifications may not contain requirements for the magnetic field and its reduction, the major RFI/EMI problems for any system are associated with the induction or magnetic field.

Therefore, the design engineer's attention must be oriented toward minimizing the generation of spurious magnetic energy by using techniques such as torroidal pot cores for transformers and inductors or retard coils. Transposition or the light uniform twisting of conductors will also reduce external flux fields. When an analysis indicates that care has been provided in design to restrict the generation of spurious magnetic fields, then the shielding material requirements can be reduced with shielding being required primarily for electric fields. When this design goal has been achieved, then the weight of the vehicle can be reduced by restricting shielding metals to low permeability, high conductivity materials such as aluminum, titanium, etc.

Metal	Relative Conductivity	Relative Permeability at 150 kilohertz	Penetration Loss in dB/mil at	Reflection Loss in dB/Magnetic Field
Copper	1.00	1	10 kHz -0.34 50 kHz -1.29	10 kHz -44.2 150 kHz -56.0
Steel (#1080)	0.17	1000	10kHz -4.4 50 kHz -16.9	10 kHz -8.0 150 kHz -18.7
Aluminum	0.61	1	50 kHz -1.01	No measureable reflection losses

Table 1. Shielding Parameters for Selected Metals.

This article was written for ITEM 85 *by Dr. Anthony W. Laine, Rockford, IL.*