Shielding Theory and Practice (Using Kirchhoff's Laws)

Kirchhoff's laws are used to develop the attenuation characteristics of shielding materials to the E and H vectors of an incident electromagnetic field.

GEORGE M. KUNKEL
SPIRA MANUFACTURING CORP.
NORTH HOLLYWOOD, CA

INTRODUCTION

The shielding of electromagnetic (EM) fields using Kirchhoff's laws provides the attenuation characteristics of the E and H vector fields at the transmitted side of a shielding barrier. This information provides the value of the E and H fields adjacent to the barrier. The results are also used to approximate the shielding effectiveness of a gasketed joint.

The development of the theory begins with the displacement current which exists between a pair of wires carrying a differential signal. The value of the displacement current in volts per meter is the difference in voltage divided by the distance between the wires. This definition is used to develop the field strength at any distance, R, from the pair of wires.

The attenuation characteristics of shielding materials are developed as a function of: the current induced into the material by the field, the impedance of the barrier, and the skin effect (or back EMF) created by the induced current in the barrier material.

The current induced into the shielding material by the field is also used to predict the shielding effectiveness of a gasketed joint.

The term "shielding quality" is defined and used to characterize the attributes of shielding materials and gasketed joints.

GENERATION & PROPAGATION OF EM WAVES

Radiated electromagnetic (EM) fields are generated by passing current through a wire or wire pair. The pattern generated by passing current through a wire pair is similar to that generated by an electric dipole antenna. This pattern can best be illustrated by examining a pair of plates being charged by a voltage source.

Figure 1 illustrates a set of plates

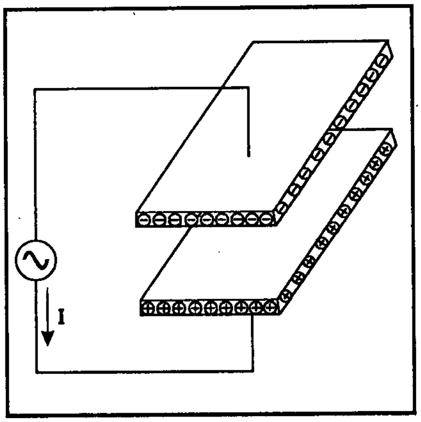

FIGURE 1. *Current Pattern.*

opposite each other with a voltage source tied between them. The current that flows through the wire comes from the top plate and is stored in the bottom plate. The over presence of the electrons on the bottom plate is illustrated by "+" and the absence of electronics on the top plate is illustrate by "-." This creates an electromagnetic field which is illustrated in Figure 2. As shown, a field exists between the plates. The magnitude of the E field is equal to the voltage differential between the plates divided by the distance between the plates in meters. The resultant E field is in volts/meter (e.g., a set of parallel plates is used to perform E field susceptibility testing to MIL-STD-461/462).

As is illustrated in Figure 2, the lines of flux in the center of the plates are straight and flow from the bottom to the top plate. At the edges they bow out, where the fields or lines of flux repel each other, forcing the bowing. The field that bows out is an EM field where the E vector quantity is equal to the voltage divided by the length of the force line in meters (i.e., if the point of concern is one meter from the set of plates, the E field would be the voltage across the set of plates divided by the circumference of the circle, or approximately E/3.1). The magnetic or H field is approximated by the following equation:

$$H = 2\pi RE/377\lambda \quad R \le \lambda/2\pi$$
$$= E/377 \quad R > \lambda/2\pi$$

Where
R = Distance from dipole antenna to barrier (m)
λ = Wavelength = c/f
c = $3 \cdot 10^{-8}$ m/sec
f = Frequency (Hz)

SUPPRESSION OF EM WAVES

When a shielding barrier is placed in the path of the EM field, the force of the field causes current to flow in the barrier. As illustrated in Figure 3, the excess electrons in the bottom plate create a force on the electrons in the barrier. This force causes the electrons to flow away from the point of contact. In a similar manner, the lack of electrons on the upper plate will create an excess of electrons on the barrier at the upper point of contact. This current flow is classified as the *surface current density* (J_S) in amperes/meter, and is approximately equal to the H field incident to the barrier. The current flowing in the barrier is attenuated by the skin depth where the current on the transmitted side is equal to $J_S e^{-d/\delta}$. The field emanating from the barrier is equal to the following:

$$H_T = J_S e^{-d/\delta}$$
$$E_T = H_T Z_B$$

Where
E_T = Transmitted E field (V/m)
H_T = Transmitted H field (A/m)
Z_B = Impedance of barrier (Ω)
= $(1 + j)/\sigma\delta(1 - e^{-d/\delta})$
d = Thickness of barrier (m)
δ = Skin depth (m)
= $(2/\omega\mu\sigma)^{1/2}$
σ = Conductivity of barrier material (Mhos/m)
ω = $2\pi f$
μ = Permeability of barrier material (H/m)

The conductivity (σ) and permeability (μ) of various materials are illustrated in Table 1.

SHIELDING QUALITY OF BARRIER MATERIALS AND GASKETED JOINTS

The shielding quality of a shielded barrier is defined as follows:

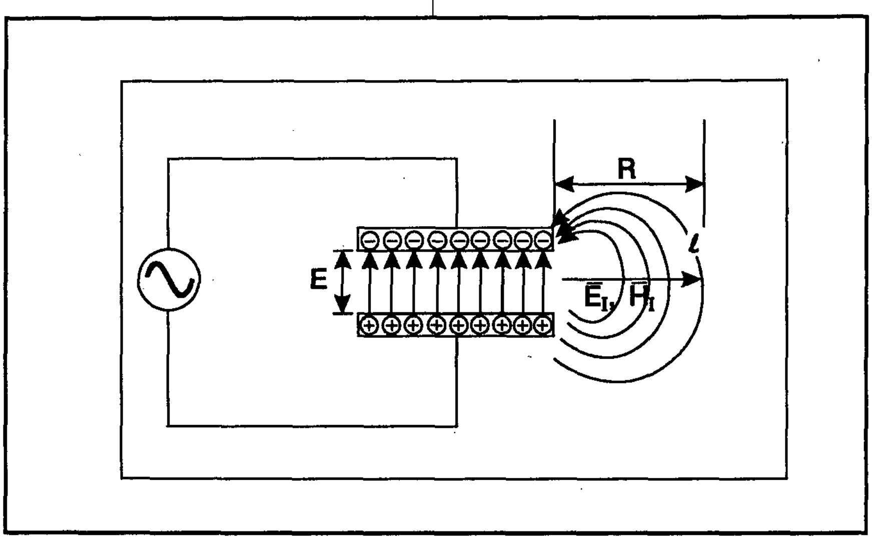

FIGURE 2. *EM Field.*

$SQ_E = 20 \log E_I/E_T$
$SQ_H = 20 \log H_I/H_T$
SQ_E = Attenuation of E field by barrier (dB)
SQ_H = Attenuation of H field by barrier (dB)
E_I = Electric field intensity at incident side of barrier (V/m)
E_T = Electric field intensity at transmitted side of barrier (V/m)
H_I = Magnetic field intensity at incident side of barrier (A/m)
H_T = Magnetic field intensity at transmitted side of barrier (A/m)

Figure 4 illustrates the same barrier containing a gasketed joint in the middle of the barrier. The current on the barrier (J_S) will be similar to that on the barrier of Figure 3. The current J_S will flow across the gasket. This current flow will create a voltage drop which in turn will generate another force field identical to the one created by an electric dipole antenna as illustrated by the parallel plates. The voltage across the joint is equal to the current J_S times the transfer impedance of the joint (Z_T) in ohm-meters, i.e.,

$E = J_S Z_T$ (Voltage across gasketed joint)

The field generated by the gasketed joint can be calculated in a manner similar to the method used to calculate the field generated by the set of parallel plates, i.e.,

$$E_T \cong E/\ell = J_S Z_T/\ell$$

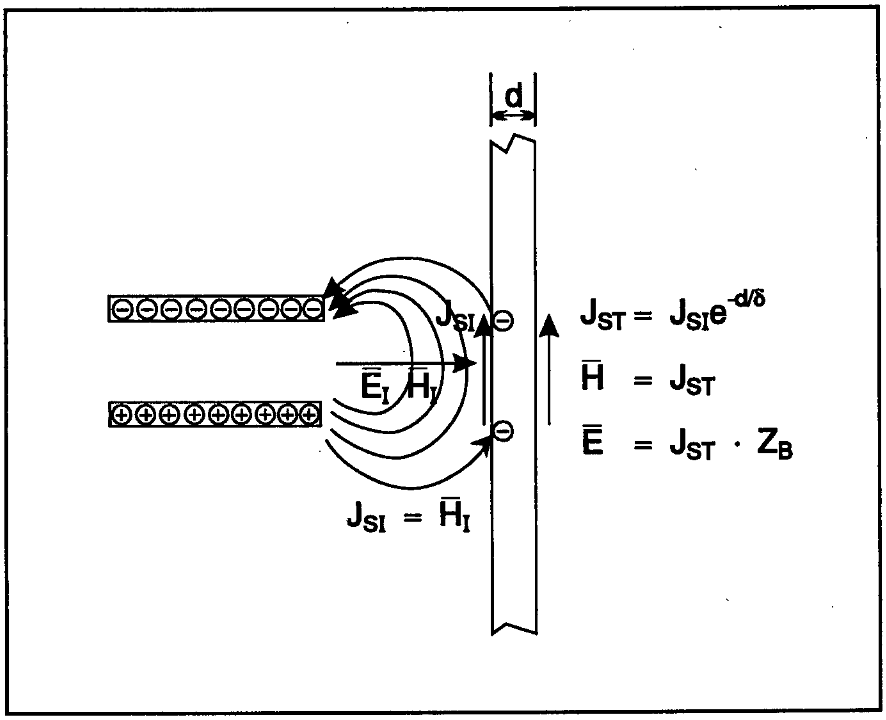

FIGURE 3. *Surface Current Density.*

MATERIAL	$\sigma \times 10^7$ (mΩ/m)	$\mu \times 10^{-6}$ (Henries/m)
Silver	6.1	1.3
Copper	5.8	1.3
Gold	4.1	1.3
Aluminum	3.6	1.3
Brass	1.5	1.3
Nickel	1.2	1.3
Bronze	1.05	1.3
Tin	0.87	1.3
Steel (SAE 1045)	0.46	1300
Lead	0.23	1.3
Stainless Steel (430)	0.12	650

TABLE 1. *Conductivity and Permeability of Various Materials.*

$H_T \cong E_T\, 2\pi R/377\lambda \qquad R \leq \lambda/2\pi$
$\quad \cong E_T/377 \qquad R > \lambda/2\pi$

The shielding quality of a gasketed joint (SQ_{GT}) is defined as follows:

$SQ_{GT} = 20 \log Z_W/Z_T \quad (Z_W/Z_T > 1)$
Z_W = Wave impedance (ohms)
$= 377\lambda/2\pi R$ (From electric dipole) $R \leq \lambda/2\pi$
$= 3772\pi R/\lambda$ (From magnetic dipole $R \leq \lambda/2\pi$
$= 377 \qquad R > \lambda/2\pi$
Z_T = Transfer impedance of gasketed joint

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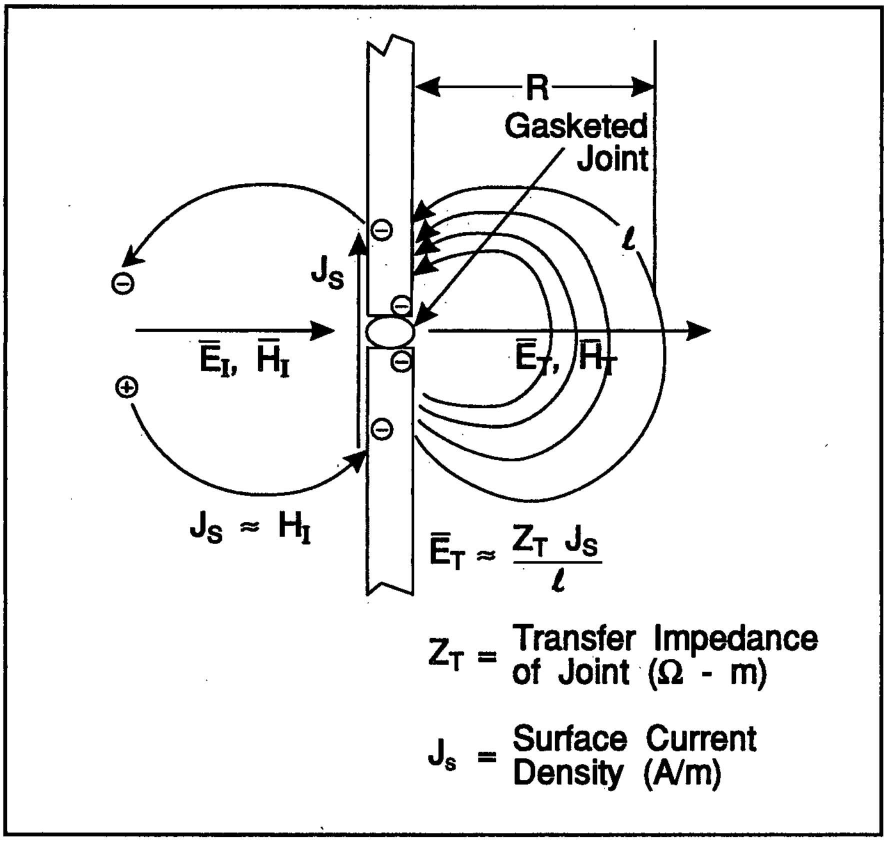

FIGURE 4. *Shielded Barrier with Gasketed Joint.*

The shielding quality of a gasketed joint approximates the shielding effectiveness of a gasketed joint when using the conditions and constraints consistent with electromagnetic field theory, where R = 1/2 meter.

SUMMARY

The use of Kirchhoff's laws to approximate the shielding of barrier materials and gasketed joints adds a significant dimension to the understanding of shielding phenomena. This understanding is in terms of the shielding of a barrier and the shielding of a gasketed joint.

The results of the analysis yields the following:

- The shielding quality of barrier materials to E and H fields.
- The field strength in terms of the E and H vector quantities which exit the barrier.
- The shielding quality of gaskets and gasketed joints. This shielding quality approximates the shielding effectiveness of a gasketed joint when constraints consistent with electromagnetic theory and test constraints consistent with MIL-STD-285 are applied.

SELECTED BIBLIOGRAPHY

Hallen, Erik. Electromagnetic Theory. New York: John Wiley and Sons Inc., 1962.

Hershberger, "Introduction to Electromagnetic Theory," Class Notes, ENGR 117 A/B, UCLA, 1961.

Hyat, William H., Jr. Engineering Electromagnetics. New York: McGraw-Hill Book Company, 1958.

Kunkel, George M., "Circuit Theory Approach to Shielding," IEEE International Symposium on EMC, Anaheim, CA, 1992.

Kunkel, George M. and Broaddus, Al, "Shielding Effectiveness Test Results of Aluminized Mylar," IEEE International Symposium on EMC, Anaheim, CA, 1992.

Ott, Henry W., Noise Reduction Techniques in Electronic Systems. New York: John Wiley and Sons, 1976.

GEORGE KUNKEL *received B.S. and M.S. degrees in engineering from UCLA. As a graduate student he was a member of the teaching staff and subsequent to graduation he taught courses on EMC design in the UCLA Extension Department. He is president and owner of Spira Manufacturing Corporation. He is a senior member of the IEEE and was Chairman of the TC-4 Technical Committee of the EMC Society of the IEEE for 17 years. He has been listed in Who's Who in the World and Who's Who in Finance and Industry. (818) 764-8222.*