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A DESIGNERS GUIDE TO SHIELDING

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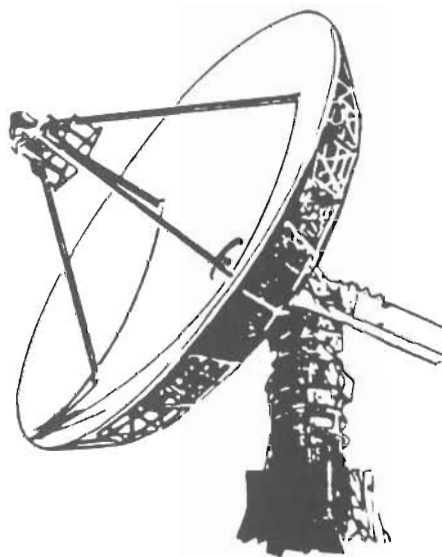
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TOM JERSE
MARK TERRIEN

**RF & Microwave
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A DESIGNER'S GUIDE TO SHIELDING

- Basics of Shielding Effectiveness
- Minimizing the Effect of Discontinuities
- Shielding Effectiveness Measurements

As the electromagnetic spectrum becomes more crowded, the need for effective shields increases. This paper presents the basic principles of shield design including the powerful concept of transfer impedance. In addition, it describes a high-dynamic range measurement system that has been successfully used on the design bench in the creation of many effective shields.

SHIELDING EFFECTIVENESS

$$S = 20 \log \left(\frac{|E|_{\text{unshielded}}}{|E|_{\text{shielded}}} \right)$$

$$S = 20 \log \left(\frac{|H|_{\text{unshielded}}}{|H|_{\text{shielded}}} \right)$$

$$S = A + R + B \quad [\text{dB}]$$

A = Absorptive Loss

R = Reflective Loss

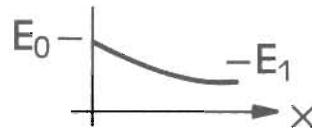
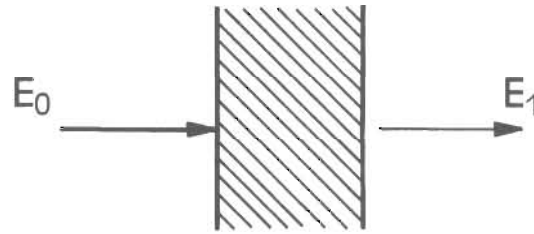
B = Multiple Reflection Factor (<0)

The definition of shielding effectiveness comes from the way it is measured. First, a field intensity is measured without the shield in place. Next, the shield is installed and the field strength is measured under the same conditions. As shown in the equations above, taking the ratio of the shielded to unshielded measurements gives the shielding effectiveness. This technique applies to both magnetic and electric fields.

The analytic calculation of the shielding effectiveness of a real-life configuration can be relatively difficult. The effectiveness depends on many factors: the material used, the type of field, the distances from the source and receiving antennas, and the nature of any discontinuities in the shield. However, analyzing simplified cases can help engineers to develop an understanding of good design practice.

For a continuous sheet of conductive material, the shielding effectiveness can be estimated by the three-term formula above. It includes the two principal mechanisms that reduce field intensity: absorptive loss (A) and reflective loss (R). (The last term, B, is a correction factor for magnetic fields that will be explained below.)

ABSORPTIVE LOSS



$$E_1 = E_0 e^{-t/\delta}$$

$$\text{where } \delta = \text{Skin Depth} = \sqrt{\frac{2}{\omega\mu\sigma}}$$

(Applies to H-Field Also)

A field propagating through a conductor is subjected to absorptive losses due to the conductor's extremely poor dielectric characteristics. This effect causes the field intensity to decrease exponentially inside the conductor. The amount of absorptive loss is determined by the conductor's skin depth which represents the distance in the conductor at which the field is attenuated by the factor $1/e$. The skin depth decreases with conductivity, permeability, and frequency. Except at low frequencies, the skin depth is quite shallow resulting in substantial absorptive losses. For example, the skin depth of aluminum at 1 MHz is only $83\mu\text{m}$, and so a 1-mm thick plate would, in theory, provide 105 dB of absorptive loss.

ABSORPTIVE COMPONENT OF SHIELDING EFFECTIVENESS

$$A = 20 \log \left(\frac{E_0}{E_0 e^{-t/\delta}} \right)$$

$$A = 8.69 \left(\frac{t}{\delta} \right) \text{ [dB]}$$

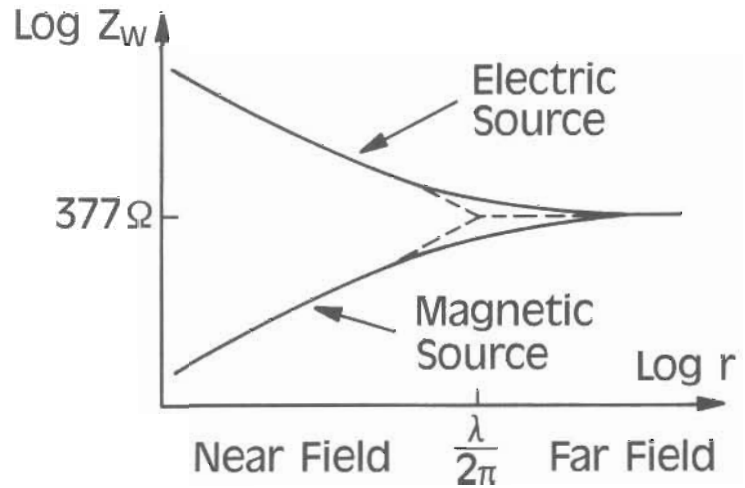
A useful rule-of-thumb for design is that 8.69 dB of attenuation is obtained for every skin depth of conductor thickness.

WAVE IMPEDANCE

$$Z_W = \frac{|E|}{|H|}$$

A Function of the Distance (r) from the Source.

$$\text{Let } r_0 = \frac{2\pi r}{\lambda}$$



Magnetic Source

$$Z_W = 120\pi \frac{r_0}{\sqrt{r_0^2 + 1}}$$

Electric Source

$$Z_W = 120\pi \frac{\sqrt{r_0^2 + 1}}{r_0}$$

A second phenomenon that contributes to the shielding effectiveness of a conductive plate is the reflective loss that occurs due to the impedance discontinuity at every boundary between the air and the metal.

The impedance of an electromagnetic wave is defined as the ratio of its electric field intensity (E) to its magnetic field intensity (H). This value depends on the characteristics of the medium containing the wave as well as the distance between the source of the wave and the observation point. The wave impedance of a plane wave in free space is 120π , or 377 Ohms. As the figure above illustrates, in the region near the source, the wave impedance depends on the type of source. Near an electric dipole there will be much more E-field than in a plane wave, and so the wave impedance will be relatively large. Conversely, near a magnetic dipole the H-field will predominate resulting in a relatively small wave impedance. In both cases, the wave impedance is a function of the distance from the source. It asymptotically approaches the plane-wave value of 377 Ohms as the distance increases. The transition between near-field and far-field behavior occurs at an approximate distance from the source of $\lambda/2\pi$.

REFLECTIVE LOSSES

Characteristic Impedance

$$Z_0 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}$$

Insulators

$$\sigma \ll j\omega\epsilon$$

$$Z_0 = \sqrt{\frac{\mu}{\epsilon}}$$

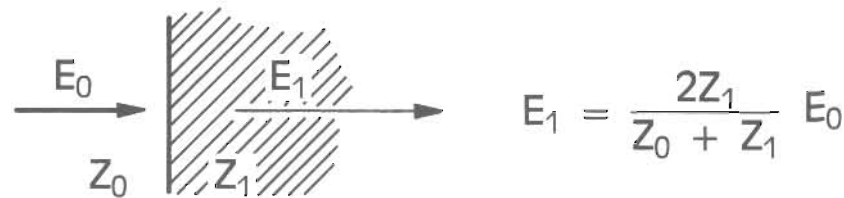
Conductors

$$\sigma \gg j\omega\epsilon$$

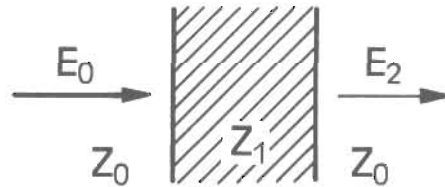
$$|Z_0| = \sqrt{\frac{\omega\mu}{\sigma}}$$

The generalized equation for the characteristic impedance of any isotropic material is given above. For large conductivities, the equation can be simplified as shown. Typically the characteristic impedance of a conductor is very small compared to the impedance of an impinging wave. For instance, the characteristic impedance of aluminum at 1 MHz is only 4.6×10^{-4} Ohms. When this value is compared with the free-space wave impedance of 377 Ohms, it is easy to see that boundary reflections can provide a significant amount of mismatch loss.

ELECTRIC FIELDS



$$E_1 = \frac{2Z_1}{Z_0 + Z_1} E_0$$



$$E_2 = \frac{4Z_0Z_1}{(Z_0 + Z_1)^2} E_0$$

Neglecting Multiple Reflections

For $Z_1 \ll Z_0$ $E_2 = \frac{4Z_1}{Z_0} E_0$

$$R_E = 20 \log \left(\frac{Z_0}{4Z_1} \right)$$

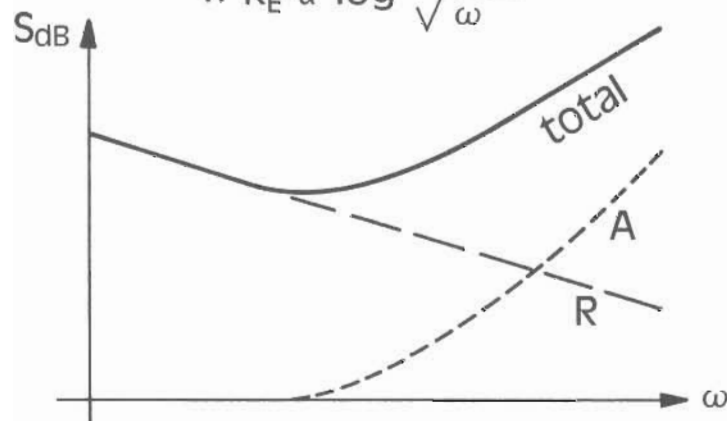
Suppose an electric field E_0 , in a wave with an impedance of Z_0 , strikes a conductor with an impedance Z_1 . Derived from the boundary conditions for electric fields, the equation above shows the amount of field (E_1) coupled into the conductor. (The rest of the energy is reflected.) An additional reflection occurs on the other side of the metal where the field exits the conductor. Neglecting what happens to the wave reflected at this boundary, the net strength of the field (E_2) emerging from the other side of the shield is shown above. Assuming the impedance of the conductor is very small, the reflective component (R_E) of the shielding effectiveness can be given in simpler form. This equation demonstrates that the smaller the conductor's characteristic impedance, the more effective the shielding.

NET SHIELDING EFFECTIVENESS FOR ELECTRIC FIELDS

$$R_E = 20 \log \left(\frac{Z_0}{4Z_1} \right)$$

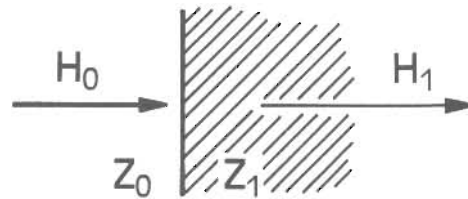
Because Z_1 characterizes a Conductor, $Z_1 \propto \sqrt{\omega}$.

$$\therefore R_E \propto \log \frac{1}{\sqrt{\omega}}$$



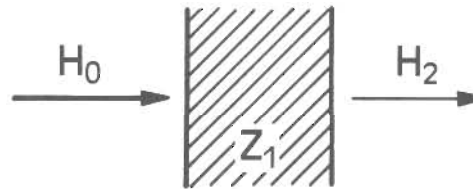
Because the characteristic impedance of a conductor increases with frequency, the reflective losses decrease with frequency. Fortunately, the absorptive losses have the opposite characteristic since skin depth decreases with frequency. Thus, in the total shielding effectiveness ($S=A+R$), the reflective losses dominate at low frequencies, and the absorptive losses dominate at higher ones. Except for thin metal coatings, a conductive sheet provides good electric-field shielding at all frequencies.

MAGNETIC FIELDS



$$H_1 = \frac{2Z_0}{(Z_0 + Z_1)} H_0$$

For $Z_1 \ll Z_0$; $H_1 = 2H_0$ (!)



$$H_2 = \frac{4Z_0Z_1}{(Z_0 + Z_1)^2} H_0$$

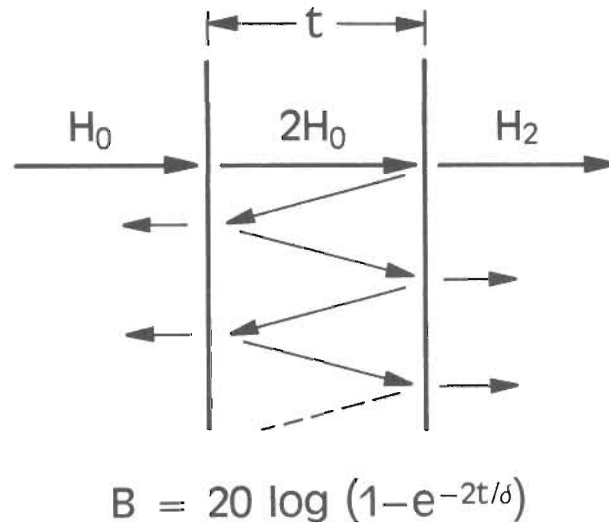
Neglecting Multiple Reflections

For $Z_1 \ll Z_0$; $H_2 = \frac{4Z_1}{Z_0} H_0$

$$R_H = 20 \log \left(\frac{Z_0}{4Z_1} \right)$$

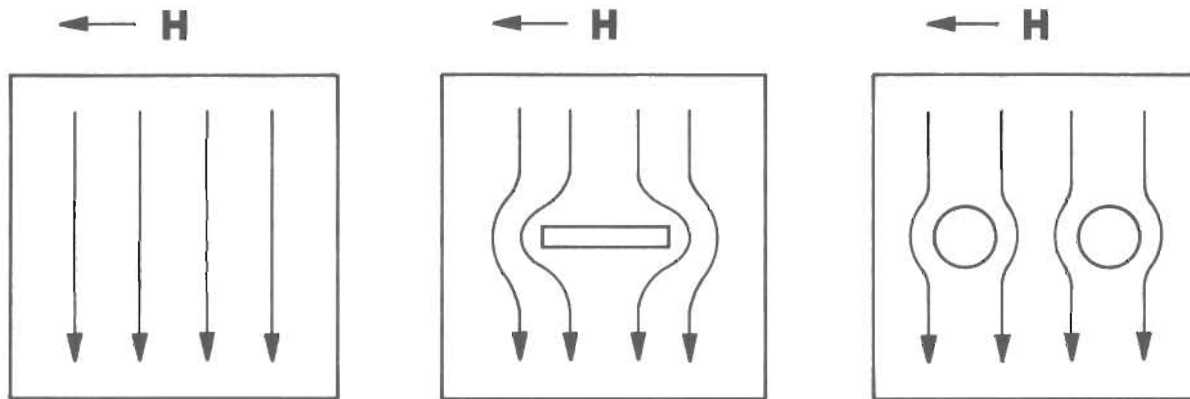
The reflective losses for magnetic fields are calculated in much the same way as for electric fields. The total reflective loss (R_H) is the same as in the electric-field case. However, because magnetic fields satisfy different boundary conditions than electric fields, the field intensities within the conductor are different. Notice that upon making the assumption of a small conductor impedance, the expression for the field inside the conductor (H_1) reduces to $H_1=2H_0$. Thus, a large magnetic field resides inside the conductor. If the absorptive losses are small, the energy reflected back as the field leaves the conductor cannot be ignored.

REREFLECTION OF MAGNETIC FIELDS



Suppose for a moment that the absorptive loss in the conductor is zero. The field inside the conductor will bounce back and forth between the conductor walls, and a small portion of the field will leak out every time the wave strikes a wall. In the limit, half the field will end up emerging from the left side of the shield; the other half will leak out the right side. Thus, in this theoretical case the reflective loss would be zero. In practice, the conductor will impart some absorptive loss to the field on each pass through. To account for this effect on these re-reflections, another term, B , is appended to the shielding-effectiveness equation. B is always negative, indicating that the reflective loss predicted without including multiple reflections is too optimistic. If the absorptive loss of the conductor exceeds 10 dB, then B can be neglected.

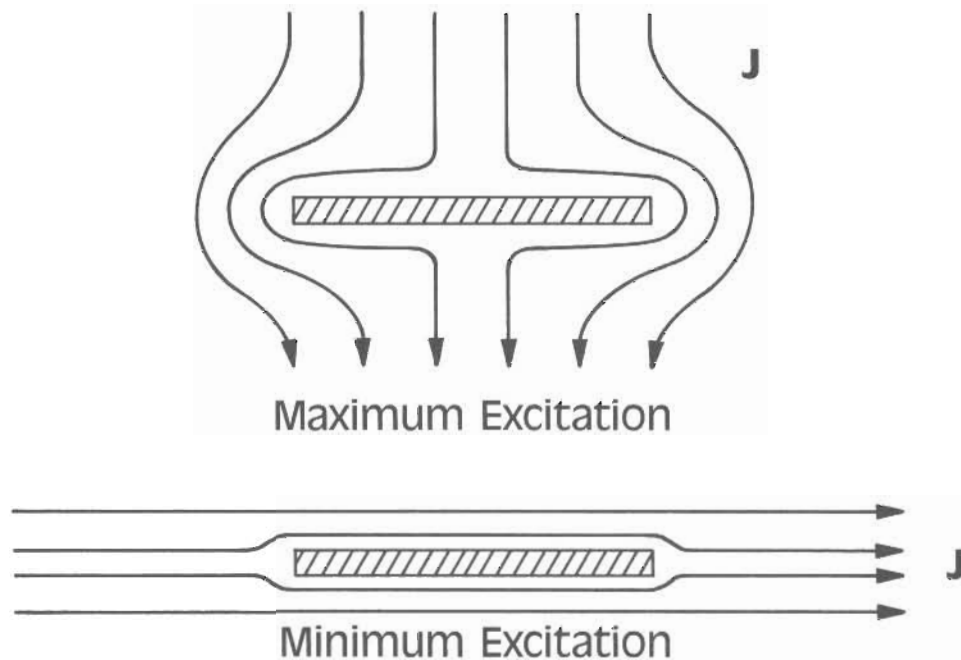
CONCEPTUALIZING THE EFFECT OF SHIELD DISCONTINUITIES:



Except for thin conductive coatings or for low-frequency magnetic fields, the combination of absorptive and reflective losses predicts a very high value of shielding effectiveness for a conductive sheet. In a real-life situation, the actual shielding effectiveness is almost always significantly less due to the presence of discontinuities such as holes and seams. The way in which these discontinuities are handled is the foremost determinant of the shielding effectiveness.

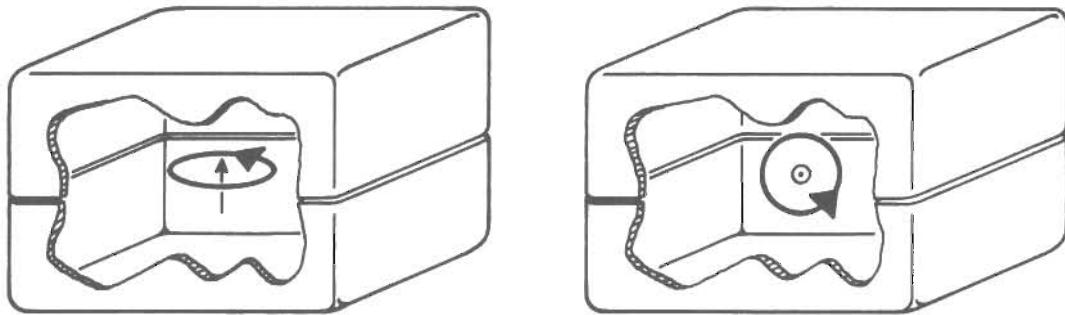
One way to conceptualize the process of shielding is to visualize the impinging field as inducing a current on the surface of the shield. If the shield is perfect, the field set up by the surface current will exactly cancel the impinging field. Any slots or holes in the shield will disrupt the surface current flow and, hence, degrade the shielding effectiveness. Thus, the best hole configurations are those that cause the minimum disturbance in the current flow.

SLOT ANTENNAS EXCITED BY SURFACE CURRENTS



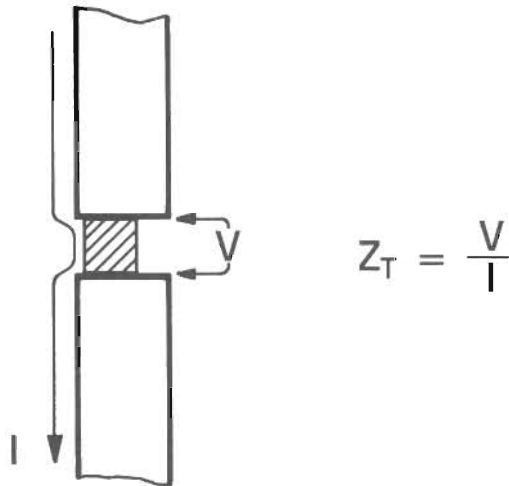
The direction of current flow with respect to the orientation of a slot can have a large impact on the amount of shielding degradation experienced. When the current tries to flow across the slot, the maximum amount of field is coupled to the other side of the shield. On the other hand, when the current flows along the length of the slot, much less field is coupled. Thus, for any arbitrary field orientation the maximum linear dimension of a hole, and not its surface area, determines its shielding effectiveness.

SEAM ORIENTATION IS IMPORTANT IN MAGNETIC SHIELDING



Sometimes, as in shielding a transformer or circuit assembly, the designer has control over the orientation of the discontinuities with respect to the fields inside the shield. As an example, consider the two-piece shield shown above where the shield halves are joined by a horizontal seam. If the circuit's current flow inside the shield is parallel to the seam, the generated magnetic field will induce surface currents on the shield that are parallel to the seam. However, if the circuit's currents are oriented perpendicular to the seam, the shield's surface currents will try to flow across the seam. Assuming the same quality of surface contact at the seams in each case, the latter case will have much less shielding effectiveness.

BASIC CONCEPT OF TRANSFER IMPEDANCE

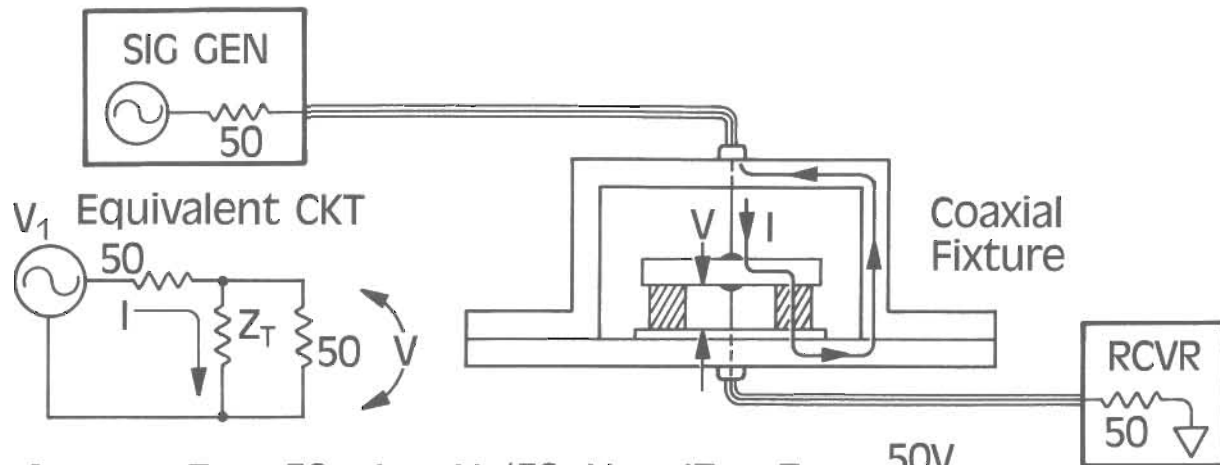


In the past, the seams between parts of a shield were joined with a large number of fasteners. This type of construction provided a considerable amount of contact pressure and relatively good electrical contact between the parts. However, for reasons of cost and aesthetics, modern packaging styles have favored the use of a minimum number of fasteners. This approach has often resulted in long seams with anomolous points of contact. In fact, the quality of the electrical contact at the seams is often the primary factor in the shielding effectiveness of a package.

Transfer impedance is a useful means of characterizing the electrical contact between parts of a shield. The concept of transfer impedance was introduced 50 years ago to characterize the performance of cables and connectors. It has subsequently been extended to include shields and shielding materials as well.

Transfer impedance relates the voltage induced on the **inside** of the shield as a result of current flowing on the **outside**. The drawing above describes a gasketed joint, but the concept applies to all types of shield interfaces. In most cases the value of transfer impedance is normalized to Ω/m by the length of the gasket.

MEASUREMENT OF THE TRANSFER IMPEDANCE OF A GASKET



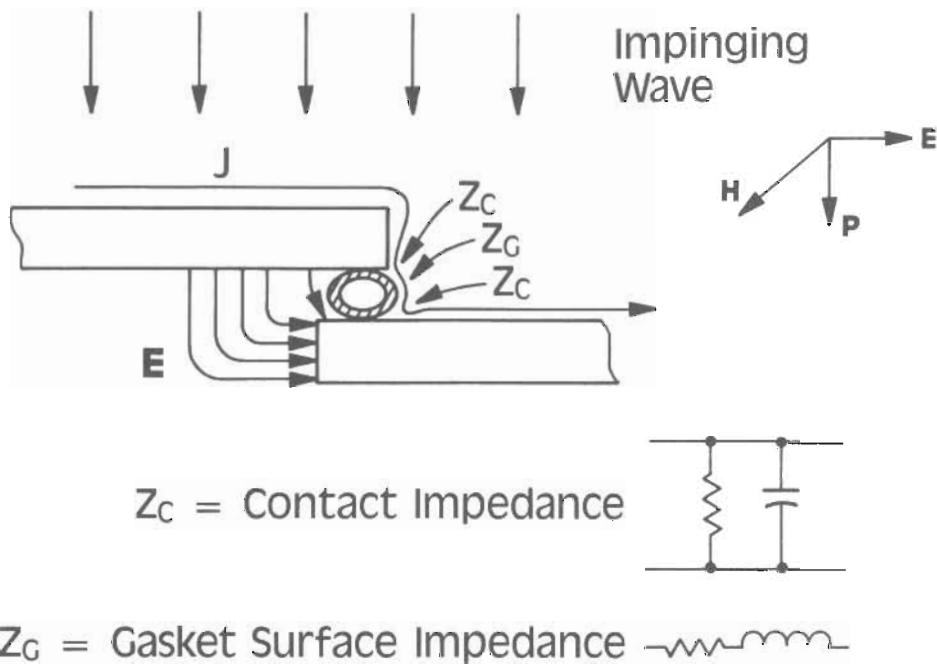
Assume $Z_T \ll 50$ $I = V_1/50$; $V = IZ_T$ $Z_T = \frac{50V}{V_1}$

Transfer Impedance is Ordinarily Normalized Per Unit Length

$$Z_{TR} = \frac{Z_T}{\ell}; \text{ Where } \ell = \text{Perimeter of Gasket}$$

The figure above shows one standard method for measuring the transfer impedance of EMI gasket material. The coaxial structure makes it simple to measure the frequency dependence of the transfer impedance. Most fixtures of this type allow pressurized air to be injected into the top chamber, enabling accurate, uniform control of the pressure exerted on the gasket under test.

GASKETED JOINT



In the arrangement shown above, the principal part of the transfer impedance is the contact impedance found where two materials touch each other. The contact impedance can be modelled as a parallel RC network. Thus, at higher frequencies the contact impedance can actually decrease due to capacitive coupling between parts of the shield. This can result in better shielding effectiveness at high frequencies. To the engineer who models the seam as a slot, this behavior can prove confusing since a slot radiates more efficiently at higher frequencies. However, the contact impedance model explains this phenomenon. Thus, the measurement of shielding effectiveness that improves with frequency can often be a salient indicator of poor contact impedance in the shield under test.

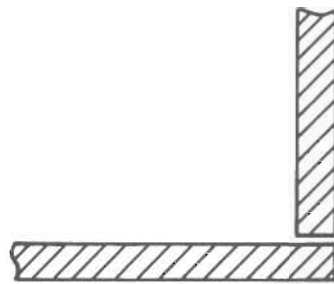
CONTACT RESISTANCE ACROSS SEAMS MUST BE KEPT LOW

IT DEPENDS HEAVILY ON:

- Pressure
- Material
- Surface Area
- Corrosion

The best way to obtain good shielding effectiveness is to reduce the real part of the contact impedance as much as practicable. Within economic constraints, one should choose a material for the surfaces of the shield part which has a low contact resistance. Because contact resistance is usually a strong function of applied pressure, the mechanical design of the shield must guarantee that adequate pressure exists even with worst-case dimensions on all the parts.

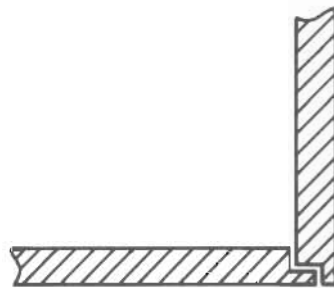
SEAMS



Bad



Bad



Better



Better

As shown in the examples above, increasing the contact surface area at the seams can also significantly reduce the transfer impedance. The contact area should also have a certain amount of surface roughness because a surface that is too smooth might not have enough microscopic points of contact.

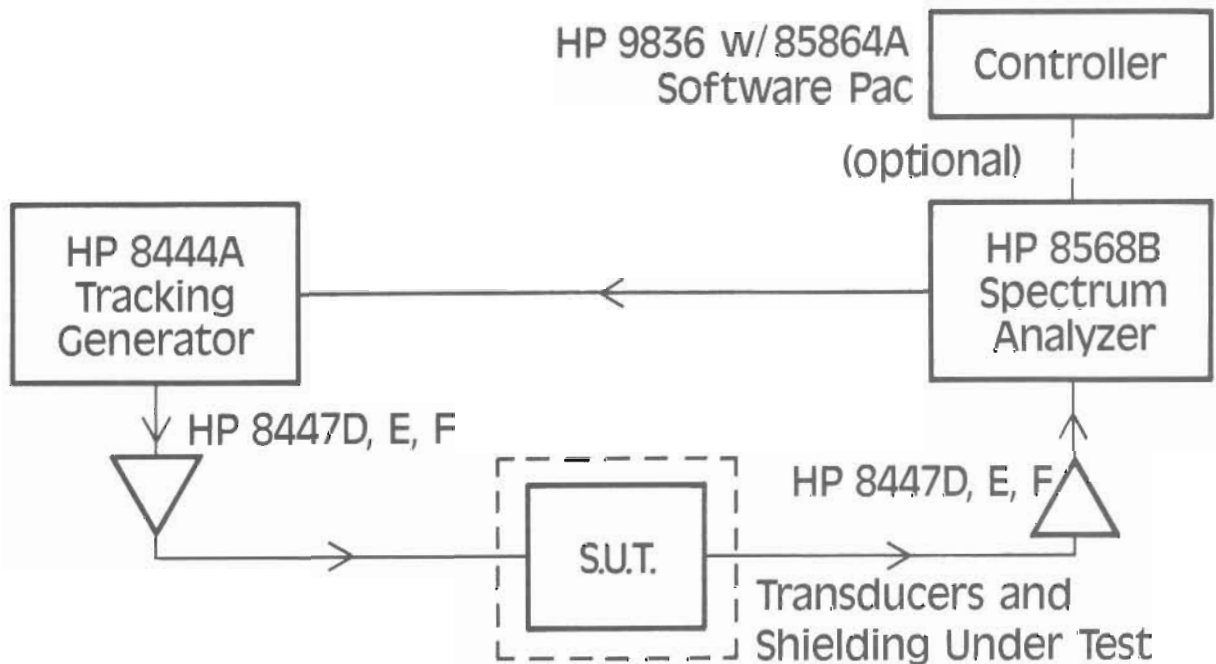
WHEN DESIGNING A SHIELDING SYSTEM, INTERMETALLIC CORROSION MUST BE CONSIDERED

ELECTRODE POTENTIALS (25°C; MOLAR SOLUTIONS)

Anode half-cell reaction	Electrode potential in volts	
Au → Au ³⁺ + 3e ⁻	+ 1.50	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="margin-bottom: 10px;">↑ Cathodic (noble)</div> <div style="margin-bottom: 10px;">Reference</div> <div style="margin-bottom: 10px;">↓ Anodic (active)</div> </div>
2H ₂ O → O ₂ + 4H ⁺ + 4e ⁻	+ 1.23	
Pt → Pt ⁴⁺ + 4e ⁻	+ 1.20	
Ag → Ag ⁺ + e ⁻	+ 0.80	
Fe ²⁺ → Fe ³⁺ + e ⁻	+ 0.77	
4(OH) ⁻ → O ₂ + 2H ₂ O + 4e ⁻	+ 0.40	
Cu → Cu ²⁺ + 2e ⁻	+ 0.34	
H ₂ → 2H ⁺ + 2e ⁻	0.000	
Pb → Pb ²⁺ + 2e ⁻	- 0.13	
Sn → Sn ²⁺ + 2e ⁻	- 0.14	
Ni → Ni ²⁺ + 2e ⁻	- 0.25	
Fe → Fe ²⁺ + 2e ⁻	- 0.44	
Cr → Cr ²⁺ + 2e ⁻	- 0.74	
Zn → Zn ²⁺ + 2e ⁻	- 0.76	
Al → Al ³⁺ + 3e ⁻	- 1.66	
Mg → Mg ²⁺ + 2e ⁻	- 2.36	
Na → Na ⁺ + e ⁻	- 2.71	
K → K ⁺ + e ⁻	- 2.92	
Li → Li ⁺ + e ⁻	- 2.96	

The avoidance of surface corrosion is an important consideration in shield design. Wherever possible, dissimilar metals should not be placed in intimate contact. This avoids the galvanic cell created by such non-homogenous contact. The larger the cell potential, the greater is the likelihood of corrosion. If for other reasons it is necessary to use dissimilar metals, the ones chosen should be relatively close to each other in the electromotive series. Whatever the metal system used, the shield design should be exposed to high temperature and humidity conditions and then tested for shielding degradation.

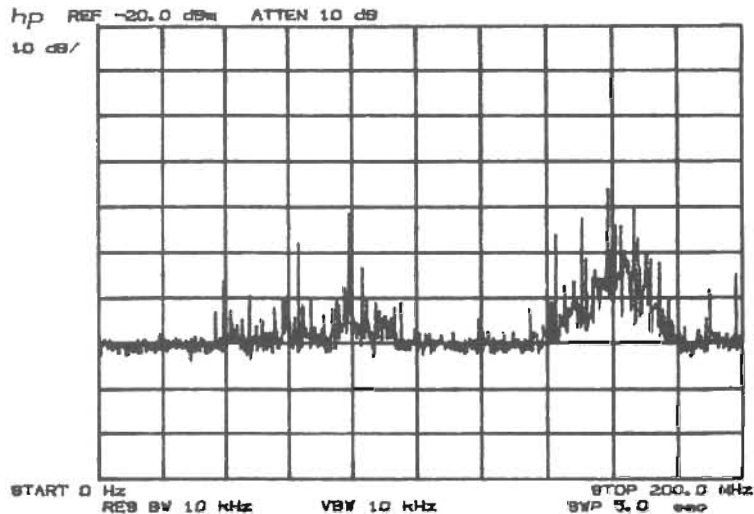
A SHIELDING EFFECTIVENESS MEASUREMENT SYSTEM



Spectrum analyzer based measurement systems are effective tools for making broadband shielding effectiveness measurements of circuit enclosures and cabling. The total system is a versatile evaluatory tool in benchtop, screen room and open site test areas; only transducer changes are required to match specific test conditions.

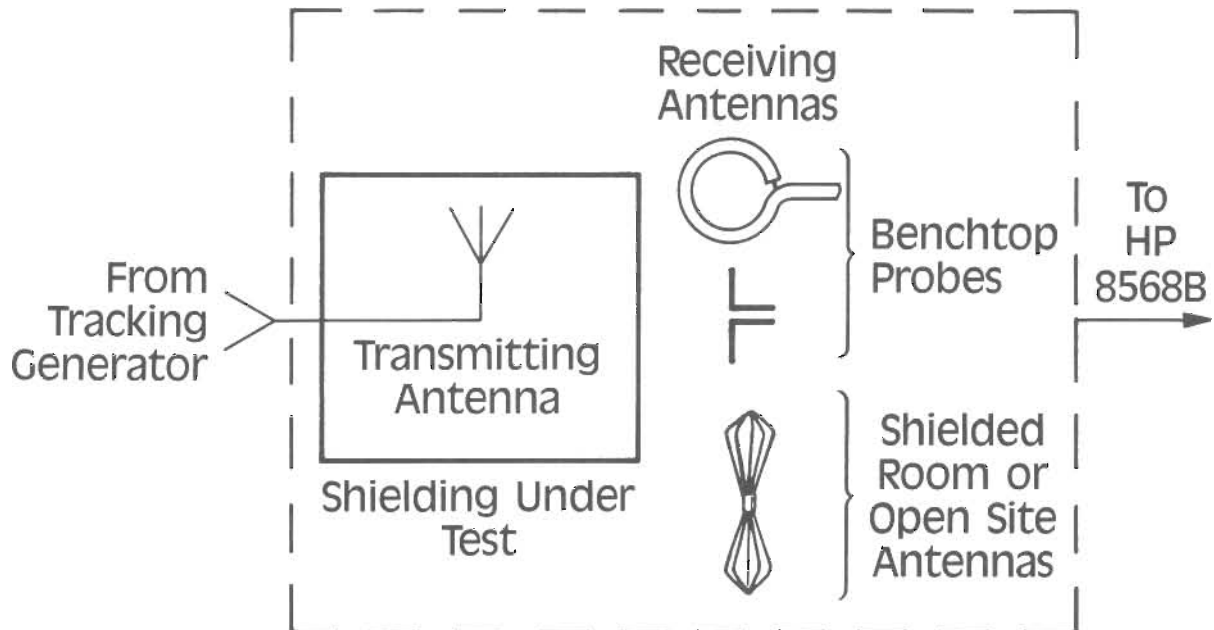
Swept measurements are made with a source that sweeps synchronously with the spectrum analyzer input frequency. Dynamic range can be increased as necessary with external amplification. Data may be taken manually or automatically with an external controller; use of the new HP 85864A EMI software package can simplify data display and storage in benchtop as well as EMI environments.

SWEPT MEASUREMENT OF RADIATION FROM A SHIELDING DISCONTINUITY



Swept broadband shielding evaluations minimize test times and improve overall measurement quality. Measurements with a tuned single frequency receiver would require a greater amount of time and would render incomplete results. For example, narrowband emissions from high-Q shielding defects that can easily be missed in a single frequency tuned measurement are easily uncovered with this swept system. Using a tracking generator eliminates the need to make multiple analyzer sweeps of certain types of circuitry. For instance, proper relative amplitude measurements are difficult to make on digital circuitry and swept L.O.'s. The amount of energy radiated from digital circuitry varies as a function of time and clocking rates; radiation is only measured from a sweeping L.O. when the radiating frequency matches the input frequency of the swept analyzer.

EVALUATION OF SHIELDING EFFECTIVENESS USING BROADBAND ANTENNAS

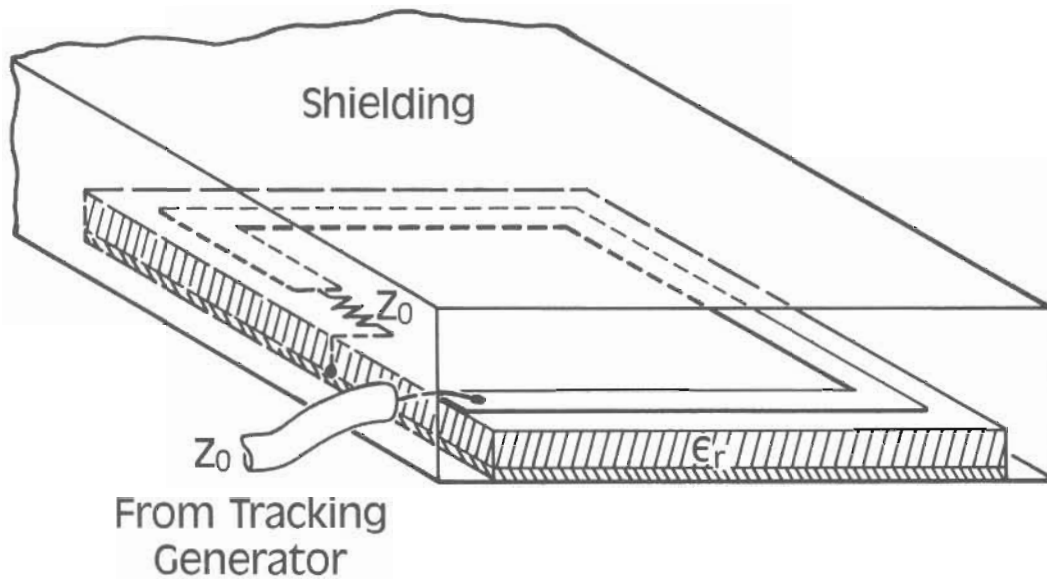


Transmitting and receiving transducers are critical elements of a broadband relative amplitude measurement system. Impedance, variability in physical size and ease of use are important considerations in choosing a proper antenna. Relative testing requires either antennas that have consistent performance in different physical locations or a well-characterized test site with a known effect on the antenna.

Tracking generator driven transmitting antennas can be used to evaluate shielding independent of the circuitry to be enclosed with that shielding.

A variety of receiving antennas are available for both benchtop and EMI environment testing. Analytically well-understood structures are preferable in benchtop operation for ease of analysis.

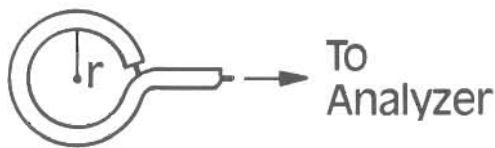
MICROSTRIP TRANSMITTING ANTENNA



A recommended broadband transmitting structure is a 50 ohm microstrip trace terminated in its characteristic impedance. These antennas are inexpensive, easy to fabricate in a variety of shapes and maintain their input characteristics over the entire operating range of the tracking generator. Microstrip design curves are readily available; low dielectric constant material and long lengths of line maximize the radiation. Low radiation efficiency is the major tradeoff for the broadband operation. Measurement repeatability requires care in antenna placement relative to the shield in question. It is necessary to have the shield of the coaxial input connector well grounded to the shielding enclosure under test.

BROADBAND RECEIVING ANTENNAS

BENCHTOP

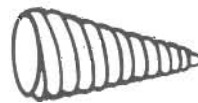


Standard
Dipoles

SCREENROOM OR OPEN SITE



Biconical



Log
Periodic

Circularly or
Linearly Polarized

Various
Broadband Antennas

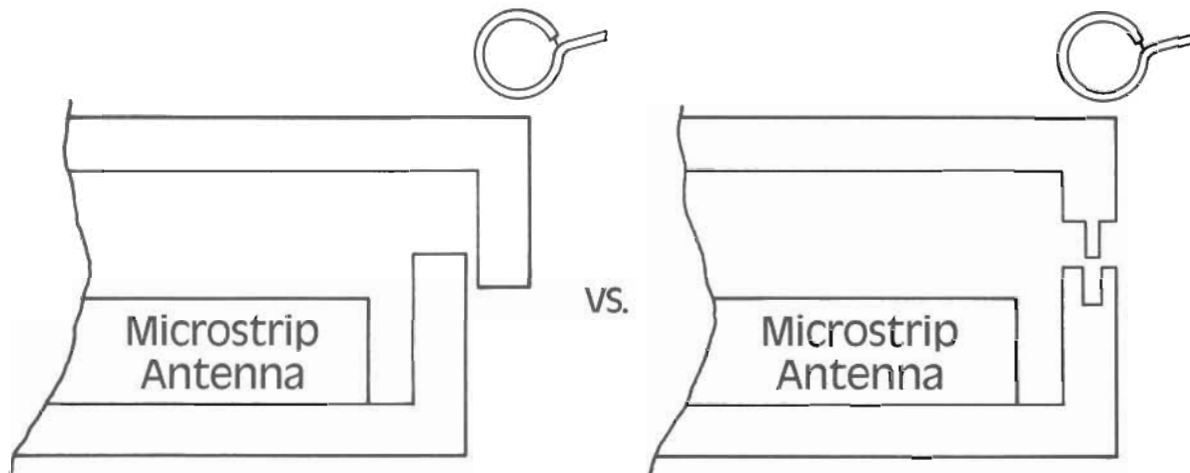
Traditional broadband antenna designs are adequate for making screen room and open site measurements, but care must be taken to avoid non-repeatable interactions between the antenna and the site. Total instrument and system evaluations are made with these antennas on the ranges mentioned above.

Benchtop testing requires smaller antennas for localized shielding effectiveness evaluation. Small electric or magnetic field sensors are the most effective transducers for this type of testing; their structural simplicity and well-analyzed performance allows easy qualitative testing and offers some conceptual insight into possible solutions to shielding problems. The small size required for mathematical rigor also allows localized detailing of shielding seams and apertures.

A magnetic field sensor is strongly recommended over an electric field sensor for best repeatability. Electric field sensors are more affected by cabling placement, radiation proximity and handling than their magnetic counterparts. In addition, the effective area of a magnetic field sensor is better defined than that of an electric field sensor. Properly shielded magnetic loops provide excellent electric field rejection and acceptable sensitivity.

BENCHTOP SHIELDING EFFECTIVENESS MEASUREMENTS

EVALUATING VARIOUS PHYSICAL CONFIGURATIONS:



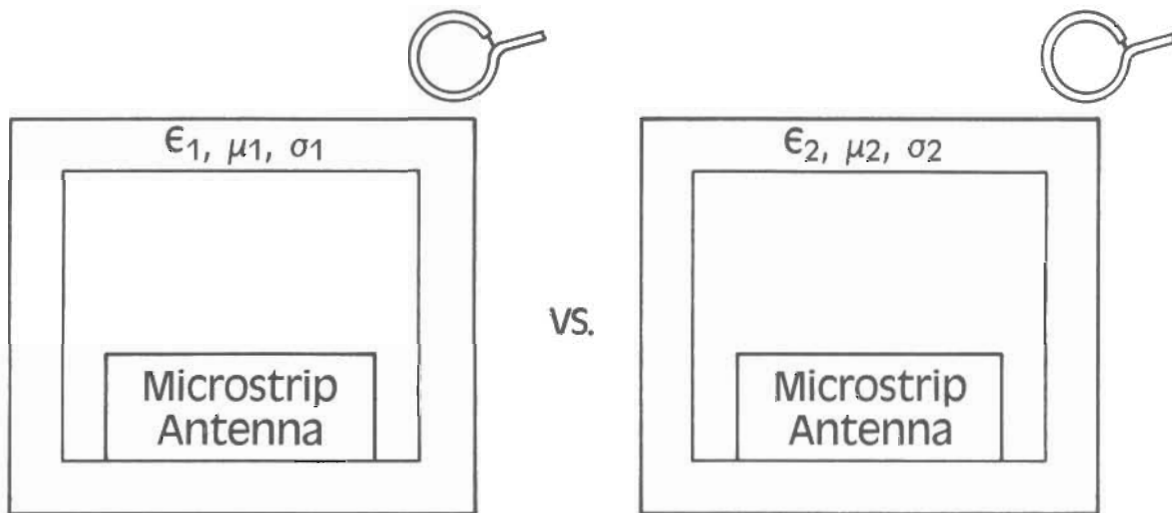
- Overall effectiveness of different seam configurations
- Localized shielding discontinuities

Benchtop testing provides information which is more useful for system troubleshooting than overall system shielding tests in screen rooms or on open sites. Time spent reducing the radiation from sub-systems of an instrument greatly reduces final system qualification time.

The most general type of benchtop testing performed involves characterization of the shielding effectiveness of various geometries. This includes evaluation of the design of instrument cases and individual circuit shields, seam configurations, and gasketing. Swept, benchtop measurements provide the designer with immediate feedback on shielding effectiveness; localized testing pinpoints radiation problems on an individual circuit basis.

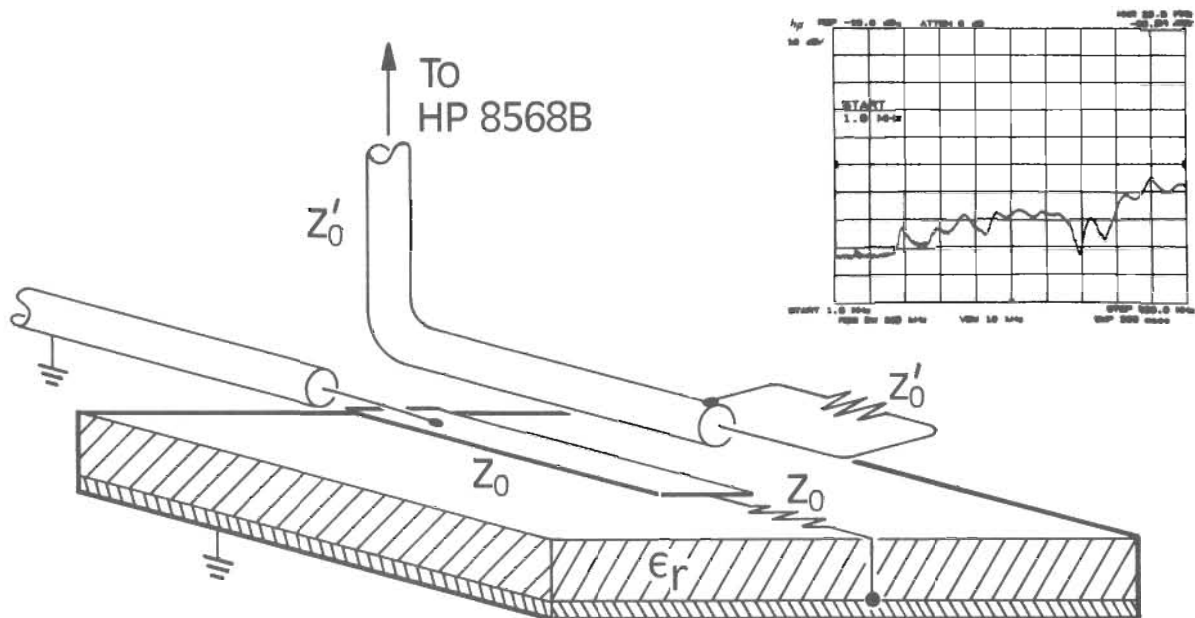
BENCHTOP SHIELDING EFFECTIVENESS MEASUREMENTS (CONT'D)

EVALUATING VARIOUS MATERIALS:



The shielding effectiveness of different materials relative to each other is best measured using identical geometries. This testing is especially useful for measuring the frequency dependency of the shielding effectiveness of magnetic material. Pre- and post-amplification is usually required when testing magnetic material due to the low frequency range of operation. When measuring larger enclosures, screen room or open site testing is often necessary.

MEASUREMENT OF COAXIAL CABLE SHIELDING EFFECTIVENESS



Proper cable shielding minimizes system design and troubleshooting time. Cable shielding problems are major contributors to overall system noise, cross talk between channels or systems and data transfer errors. High speed digital systems are one of the major challenges to quality cable shielding.

Benchtop cable shielding evaluation is a simple procedure with a swept measurement system. A microstrip line is used as the transmitting antenna and the cabling in question is the receiving antenna and is connected to the spectrum analyzer. The shielding effectiveness is indicated by the amount of signal coupled into the cabling. Direct comparisons between different cabling types can be made quickly.

MEASUREMENT REPEATABILITY

Reduce electric field sensitivity of near-field antennas

Reduce measurement layout variations

- Cable runs
- Proximity to other radiators

Reduce screen room interactions

Maintain correct pressures on gasketing when shielding dismantling is required

Maintain quality of antennas

- Match
- Insertion loss

Repeatability is a prime concern in any measurement system. Meaningful relative comparisons cannot be made if all factors affecting the measurement cannot be duplicated from test to test. The above listing contains several major contributors to non-repeatability in shielding effectiveness measurements.

One of the major causes of poor repeatability is the electric field sensitivity of the receiving antennas; the total electric field at the sensor is greatly affected by stray coupling to the system cabling and the test engineer. Variations in that coupling due to orientation also affects repeatability. Complete elimination of electric field sensitivity avoids this problem altogether. Incomplete elimination leads to probe directivity and the associated difficulty in obtaining repeatability. Variations in the physical layout of the test should also be minimized to duplicate any possible interactions between radiator and the testing environment. Observation of proper gasket use and installation procedures is mandatory.

CONCLUSION

In most cases, the success of an EMI shield depends on the way in which any discontinuities in the shield are handled. The transfer impedance model is a useful means of conceptualizing the effect of discontinuities and of understanding the qualities of a good seam.

Another necessary aid for solving shield problems is a good test system. A spectrum analyzer based swept measurement system is a versatile tool for evaluating the shielding effectiveness of instrument and circuit enclosures in benchtop, screen room and open range environments. It provides the flexibility and ease of use required in a laboratory environment. This allows the designer to spend more time minimizing the physical variables that affect proper relative measurements.

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