

**Measurement Notes**

Note 32

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**Monitor for Integrity of Seams in a Shield Enclosure**

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**ABSTRACT**

This note considers a new concept for measuring the performance of shield enclosures. It allows for the presence of aperture-like faults at unknown positions over the shield enclosure. The aperture penetration is measured in a manner appropriate to bounding the response of internal equipment. The technique leads to the location of the faults as well.

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## FOREWORD

"Oh, Kitty, how nice it would be if we could only get through into Looking-glass House! I'm sure it's got, oh! such beautiful things in it. Let's pretend there's a way of getting through into it, somehow, Kitty. Let's pretend the glass has got all soft like gauze, so that we can get through. Why, it's turning into a sort of mist now, I declare! It'll be easy enough to get through -" She was upon the chimney piece while she said this, though she hardly knew how she got there. And certainly the glass was beginning to melt away, just like a bright silvery mist.

**Through the Looking Glass**  
**by Lewis Carroll**

## I. INTRODUCTION

One designs practical shield enclosures for the protection of electronic equipment from various electromagnetic environments. One would also like to be able to measure the shield performance in such a way that the measured parameters were directly relatable to the electromagnetic coupling to the electronic equipment, and could be used to assure the satisfactory operation of that equipment. Furthermore, it would be helpful if this way to monitor the shield performance could be used regularly during the lifetime of the shield to assure its continued adequate performance.

For most purposes a sheet of metal is sufficiently conducting that diffusion of electromagnetic fields through it is not the significant problem [9]. Apertures (such as faulty seams) are in general more significant and will be considered here. In many situations conductor penetrations are the most important; other techniques apply to this case [4].

Beginning with a review of the relevant features of aperture penetration, especially for long thin apertures (slots), then the technique in [4] for bounding aperture penetration is generalized to allow for multiple apertures at unknown locations over a shield enclosure. Both the existence and location of the apertures can be determined.

## II. APERTURES IN SHIELDS

Generally for practical shield enclosures aperture penetration is dominant over diffusion penetration for coupling to interior equipment, especially when the equipment is located near such an aperture. One can model the penetrant fields by equivalent electric and magnetic dipoles. In this case the near fields (but not too near the aperture itself in units of aperture dimensions) are dominated by  $r^{-3}$  terms [9]. The dipole moments are related to the appropriate fields on the shorted (closed) aperture by a polarizability proportional to the cube of the linear dimensions, so small apertures usually do very little while large apertures can be significant.

Better than considering the electromagnetic fields per se penetrating apertures, it is more directly related to the interference problem to consider the resulting source terms for the internal equipment. As discussed in [4] an appropriate canonical problem to consider is that of a wire passing by an aperture. As in Figure 2-1 there are two equivalent sources, a series (longitudinal) voltage source  $V_s$  related to the short-circuit magnetic field  $\vec{H}_{sc}$ , and a parallel (transverse) current source  $I_s$  related to the short-circuit displacement vector  $\vec{D}_{sc}$  (or electric field). In the near field of the aperture (but not too near the aperture) these terms are proportional to the time derivative of the associated short-circuit fields. In spatial terms the dependence is  $r^{-2}$  where  $r$  is the distance from the aperture to the wire. This can be seen by integrating an  $r^{-3}$  field over a distance comparable to  $r$ , or by direct appeal to canonical problems [9].

These sources are important in that they are part of the equations used to bound the propagation of signals through subshields as part of the general topological decomposition of complex systems as a product (or convolution in time domain) of matrices in the good-shielding approximation [3-5]. In the context of apertures, since the source terms depend on the distance of a conductor from the aperture, it is useful to define an exclusion volume as indicated in Figure 2-1 [4]. One can define this exclusion volume somewhat arbitrarily (including zero if conductors are allowed to come right up to the aperture plane), but its purpose is to provide a basis for defining the maximum values that the source terms may achieve for any allowed position of conductors near the aperture (on the transmission side). In terms of normalized source coefficients these are [4]

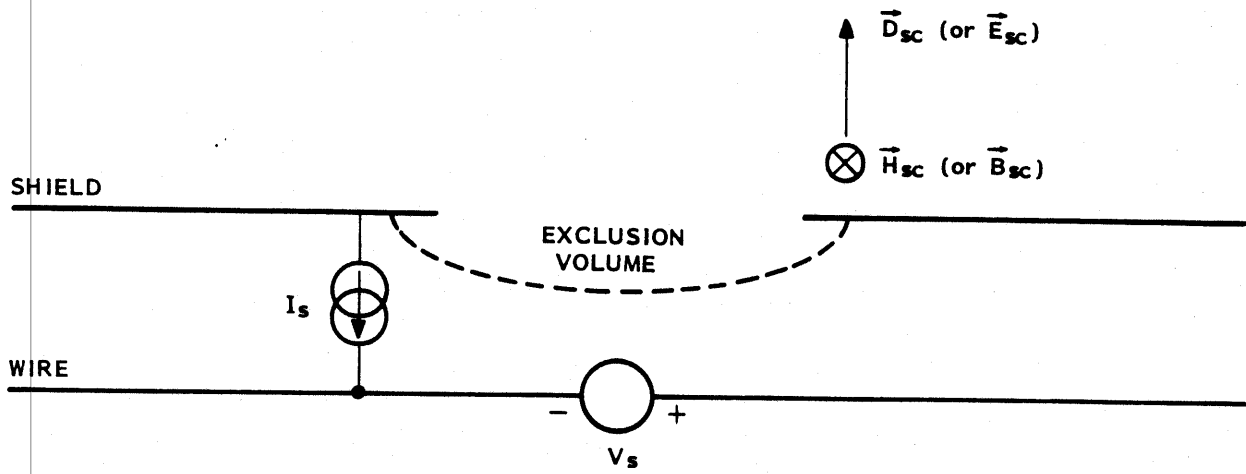


Figure 2-1. Wire Passing by an Aperture

$$\begin{aligned} \tilde{v}_s &= \frac{\tilde{V}_s}{a Z_0 \tilde{H}_{sc}} = \text{voltage source coefficient} \\ \tilde{i}_s &= \frac{\tilde{I}_s Z_0}{a \tilde{E}_{sc}} = \text{current source coefficient} \\ Z_0 &= \sqrt{\frac{\mu_0}{\epsilon_0}} = \text{characteristic impedance of free space} \end{aligned} \quad (2.1)$$

$\sim$  = Laplace transform (time  $\rightarrow$  complex frequency)

$a$  = some characteristic dimension of the system of concern.

Here  $\tilde{H}_{sc}$  is taken in a direction to maximize  $|\tilde{v}_s|$  and  $\tilde{E}_{sc}$  is of course the component normal to the surface. For wire-to-wire coupling through the aperture the coefficients are similarly defined [4].

For present purposes let us consider the aperture of concern to be a thin slot, such as is appropriate for a fault in a seam of a shield enclosure. Such a slot might be modeled as an ellipse, for which the case of the short-circuit magnetic field parallel to the long dimension of the slot is most important. In this case, let the wire be transverse to the slot for maximum coupling. This is a key point for diagnosing the presence of such a fault in a shield; the sensing wire should run across the slot, not be parallel to it. If the slot is not resistively loaded, then for frequencies below the slot half-wave resonance the dominant coupling to the wire is proportional to the time derivative of the short-circuit magnetic field parallel to the slot (or the short-circuit surface current density transverse to the slot).

An important aspect of the development in [4] is the point that

$$\begin{array}{ccc} \text{electric parameters} \left| \begin{array}{l} \text{outside} \\ \text{inside} \end{array} \right. & \longrightarrow & \text{magnetic parameters} \left| \begin{array}{l} \text{inside} \\ \text{outside} \end{array} \right. \\ \text{magnetic parameters} \left| \begin{array}{l} \text{outside} \\ \text{inside} \end{array} \right. & \longrightarrow & \text{electric parameters} \left| \begin{array}{l} \text{inside} \\ \text{outside} \end{array} \right. \end{array} \quad (2.2)$$

This is reflected in (2.1) or in terms of wire-to-wire coupling through apertures in the form [4]

$$\begin{aligned} V|_{\text{outside}} &\longrightarrow I_s|_{\text{inside}} \\ I|_{\text{outside}} &\longrightarrow V_s|_{\text{inside}} \end{aligned} \tag{2.3}$$

This cross-association of electric and magnetic parameters seem fundamental to understanding shielding. One way to look at this is that the BLT equation [2] uses wave variables which are linear combinations of voltage and current. This allows the separation of waves on one side of topological boundaries from those on the other side via a scattering matrix. Inherent in this is the possibility of electric parameters on one side producing magnetic parameters on the other side, and conversely. Another way to look at this is through the concepts of transfer impedance and transfer admittance [9], although the latter parameter may sometimes be better cast in terms of charge than voltage as the exciting term on the first side of the boundary.

### III. ILLUMINATION OF SHIELD EXTERIOR SURFACE AND MEASUREMENT OF RESULTANT INTERIOR SOURCES

#### A. Loops and Shields

We are here concerned with thin slots (seams) in shields for which the short-circuit magnetic field or surface current density is the appropriate excitation on the shield exterior. One excitation technique which has been proposed is a loop surrounding the shield [7]. This is most appropriate for low frequencies for which the loop is not resonant. In this case there is still the question of how large the loop should be compared to the shield dimensions to produce some sort of uniform magnetic field (incident or total) over the shield enclosure. Furthermore, it would be desirable to extend the frequency response to higher frequencies for which wavelengths are smaller than the shield dimensions.

On the inside of the shield the problem is somewhat similar. It has been proposed to place a loop inside the shield to enclose the maximum magnetic flux [6,8]. Since this is related to the line integral of the electric field around the loop, then at low frequencies this represents a maximum open-circuit voltage around some loop (neglecting multiple turns) which might be induced on equipment placed inside the shield. This includes not only aperture, but diffusion, contributions as well. Again at higher frequencies the loop can become resonant, destroying such a simple relationship to the internal electric field near the shield walls.

At this point we can note that transmitting from an external loop and receiving with an internal loop is only one way to look at this problem. One can also transmit from the inside and receive on the outside. These two procedures are equivalent under the usual requirements of reciprocity. Which technique is preferable often depends on other considerations such as the signal-to-noise ratio.

#### B. SCUTUM

Let us now extend the considerations of Section 2 in the direction of the aforementioned loops. Consider the external loop, but now deform it to be quite close to the exterior of the shield. Let this wire be maintained at a constant spacing from the shield walls so that it may be considered as a transmission line, of which the shield walls are an integral part. For this



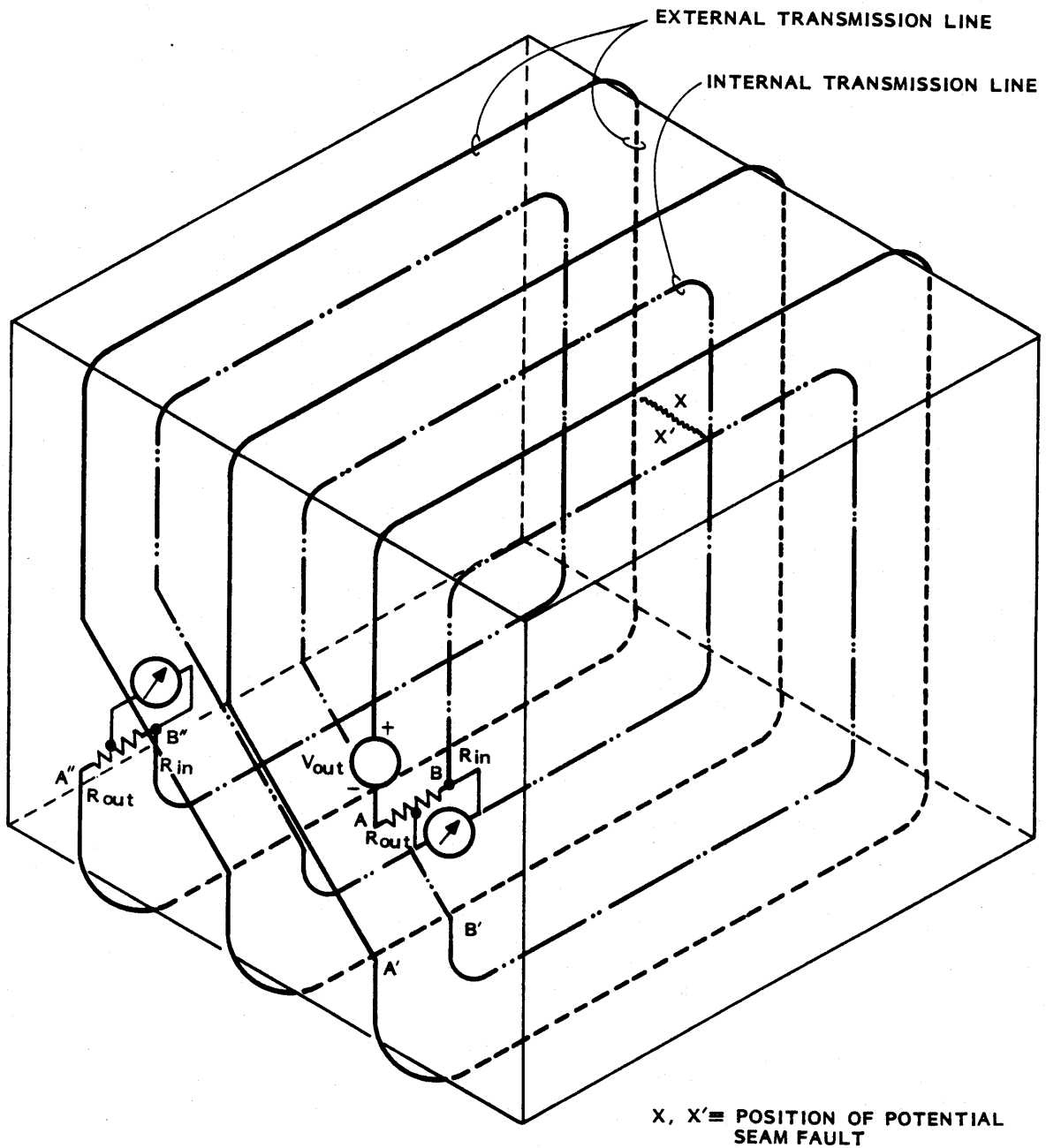
purpose let the spacing of the wire from the shield wall be small compared to both the radian wavelength and the radii of curvature of the shield walls near the wire.

As illustrated in Figure 3-1 let us start the external transmission line at A and wrap it around the shield at a uniform spacing  $a$  from the shield, returning to a position A' near A. At A drive the wire with respect to the shield with a voltage  $V_{out}$  which might in general be CW or a pulse of some specified waveform. Let the other end of the wire A' be terminated to the shield in a constant resistance  $R_{out}$  equal to the characteristic impedance of this transmission line. In this case we have established a wave propagating in one direction (from A to A') around the shield exterior. The velocity of the wave is either the speed of light  $c$  if all the dielectrics are air, or somewhat less if other insulating dielectrics are used.

As the wave propagates around the shield there is a surface magnetic field, or equivalently a surface current density which extends to both sides of the wire a distance on the order of  $a$ . The actual distribution of this surface magnetic field (with apertures closed (shorted)) is readily calculated as in [1]. So a strip of width say  $2a$  or somewhat more on the shield is effectively illuminated.

Now turn our attention to the inside of the shield. Let us begin a similar wire at B (near A, except on the inside) and continue around the inside paralleling the external wire and ending at B' (near A', except on the inside). This interior wire is spaced a distance  $b$  from the shield walls and has its own characteristic impedance  $R_{in}$  with respect to the shield walls as a transmission line. The propagation velocity is also  $c$  or somewhat less depending on the use of insulating dielectrics.

Now perform a gedankenexperiment. Let a fast-rising pulse, say approximately a step function, be introduced on the external transmission line at a. It propagates along the external transmission line until it reaches some fault in the shield at some position, say X. At the corresponding position X' on the internal transmission line a voltage source  $V_s$  is induced sending a signal of voltage  $\pm V_s/2$  propagating in both directions away from the fault with opposite polarities for the two waves. Assuming that the fault is a thin slot perpendicular to the two wires the coupling is maximized, and



ONE OF 3 PAIRS (EXTERNAL/INTERNAL) OF TRANSMISSION LINES IS INDICATED. THE 3 PAIRS WRAP AROUND THE ENCLOSURE IN 3 "ORTHOGONAL" WAYS. NOTE LOCAL CROSSINGS ARE AT RIGHT ANGLES.

Figure 3-1. SCUTUM Concept

it is dominantly the external current (magnetic field) producing the internal voltage (electric field).

The two internal waves propagate away from X' until they reach B and B'. Let us monitor (measure) these internal waves at these positions, say by a transient recorder with two inputs, say both terminated in the characteristic impedance of the internal transmission line. We now have available to us an important piece of information. Knowing the relative times of arrival of the signals at B and B' and the propagation speed of the internal transmission line we can readily locate X' (and X), the position of the fault. If the fault is an unloaded slot (negligible resistance across it). The internal signal is basically the time derivative of the external signal (an external step function becoming ideally an internal delta function), making time-of-arrival measurements somewhat precise.

Going a step further, note that so far the technique covers four faces of a rectangular parallelepiped, but with current in only one of two possible directions on each face. So image three such pairs of transmission lines, each pair wrapping around in a manner orthogonal to the other two pairs. Then each face is tested in two orthogonal directions. Each pair tests four faces in one direction; three pairs cover six faces in two directions (a kind of octahedral symmetry).

But why stop here? The external transmission line from A to A' paired with the internal transmission line from B to B' covers a strip or order  $2a$  or  $2b$  around the shield. Suppose now that the external wire is extended from A' to A" as a sort of helix around the shield with spacing from the wire to the previous (and subsequent) "windings" of order  $2a$ , or perhaps more, so that coupling from one "turn" to the next is acceptably small. Continue this procedure until the appropriate shield walls (4 for a rectangular parallelepiped as in Figure 3-1) are covered by this transmission lines. Then terminate this transmission line at A" in its characteristic impedance.

Considering now the internal transmission line let it be similarly extended as a quasi helix, "paralleling" the external transmission line, to B" where it is now terminated. Comparing the signals at B and B" the previous concept of locating the fault is still applicable. It remains to consider details of the spacing of the "turns" from each other and from the shield to

optimize the technique. For example, it may be desirable to have the internal and external wires not directly opposite to each other across the shield boundary. To optimize the uniformity of coupling from external to internal transmission lines their positions might be interspersed; the position of the internal transmission line might be spaced halfway between the positions of two adjacent turns of the external transmission line.

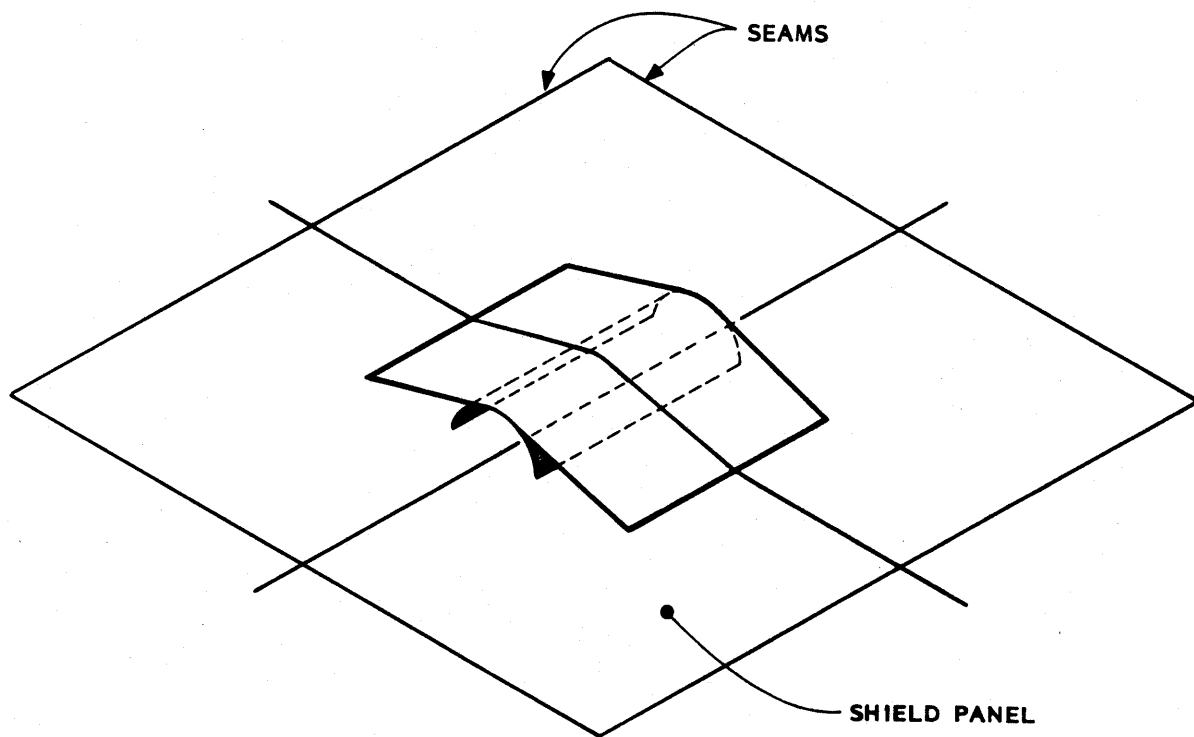
As the title of this subsection indicates, perhaps this concept needs a name. In this case we have shield closure using transitometer ultra monitor or SCUTUM (the latin word for shield) for short. Note the concept of transitometer (related to the transmission of a signal through a fault), similar to the concept of a reflectometer.

### C. Reduction of Mutual Coupling at Crossing of Transmission Line

When one of the transmission-line wires crosses another on the same side of a face of the shield enclosure there can be significant mutual coupling. Since the wires cross at right angles no magnetic flux from one wire links the other wire leading to no induced longitudinal voltage source. However, electric field from the charge on one wire does induce charge on the other wire, leading to an induced transverse current source.

In order to reduce this electric coupling at crossings the technique in Figure 3-2 can be used. Here one wire is at least partly shielded from the other at the crossing. The wire closer to the shield at the crossing goes through some sort of tunnel (or even coaxial structure if desired) in which the wire dimensions and/or spacings are adjusted to preserve the characteristic impedance of the transmission line as it passes through the crossing. The other wire passes over this tunnel with perhaps additional conductors present, and the transmission-line impedance is also preserved through the junction in this case.

Note that this isolation structure is made of good conductors which are well bonded to the shield. Such a crossing should be made to occur at some position on a shield panel which is not too close to the seams where the shield panels are joined to each other.



**MAINTAIN THE CHARACTERISTIC IMPEDANCE OF BOTH TRANSMISSION LINES CONSTANT AS THEY PASS THROUGH THE CROSSING. USE ON BOTH OUTSIDE AND INSIDE OF SHIELD.**

Figure 3-2. Reduction of Mutual Coupling at Crossing of Two Transmission Lines

#### IV. POSITIONING OF TRANSMISSION LINES

Consider now a pair of exterior and interior transmission lines (windings) as illustrated in Figure 4-1. As previously discussed the wires are spaced distances  $a$  and  $b$  from the shield wall. For simplicity now let

$$a = b \gg \text{shield wall thickness} \quad (4.1)$$

Note the coordinate system with  $y=0$  as the shield wall and the wires (transmission lines) parallel to the  $z$  axis. Now let

$$x = n\Delta, n = 0, \pm 1, \pm 2, \dots \quad (4.2)$$

be the  $x$  coordinates of the wires with

$$y = \pm a \text{ (+ for } n \text{ even, - for } n \text{ odd)} \quad (4.3)$$

as the  $y$  coordinates.

Now imagine that there is a current  $I$  in one of the wires ( $n=0$ ) and consider the fields and potentials. This has been worked out in [1]. The normalized field on the shield wall (electric or magnetic) is (with value 1 at  $x=0$ ).

$$f\left(\frac{x}{a}\right) = \left[1 + \left(\frac{x}{a}\right)^2\right]^{-1} \quad (4.4)$$

Since we wish to minimize coupling to an adjacent wire on the same side then we need

$$f_o = f\left(\frac{2\Delta}{a}\right) = \left[1 + \left(\frac{2\Delta}{a}\right)^2\right]^{-1} \ll 1 \quad (4.5)$$

In terms of potential one can obtain a more accurate estimate of the potential on one wire due to a unit potential on the first [1], but the simple estimate in (4.5) gives the basic idea.

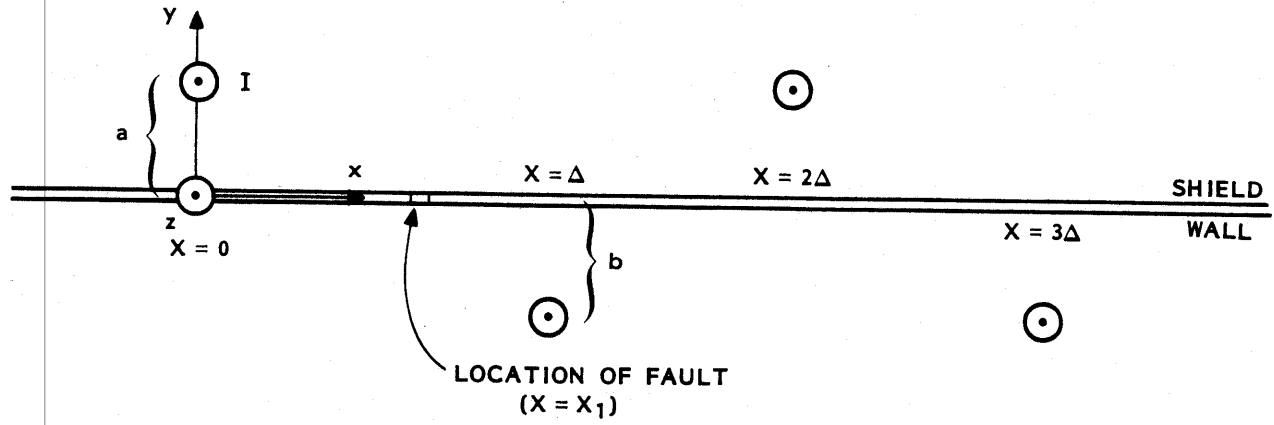


Figure 4-1. Transmission Lines in Alternating Positions on Opposite Sides of a Shield Wall

Now consider that there is some localized fault in the shield wall at  $x=x_1$  and let

$$v \equiv \frac{x_1}{\Delta} \quad (4.6)$$

The normalized field exciting this fault from the  $n=0$  wire is

$$f_1 = \left[ 1 + \left( \frac{\Delta v}{a} \right)^2 \right]^{-1} \quad (4.7)$$

The fields penetrating the fault in turn interact with the wire at  $x=\Delta$  on the other side of the shield wall. Using reciprocity considerations one can compute the relative coupling to this wire by computing the fields at  $x=x_1$  from a current in the wire at  $x=\Delta$  giving a factor

$$f_2 = \left[ 1 + \left( \frac{\Delta - x_1}{a} \right)^2 \right]^{-1} = \left[ 1 + \left( \frac{\Delta(1-v)}{a} \right)^2 \right]^{-1} \quad (4.8)$$

The coupling between the  $n=0$  wire and the  $n=1$  wire is then proportional to

$$g = f_1 f_2 = \left[ 1 + \left( \frac{\Delta}{a} \right)^2 \right]^{-1} \left[ 1 + \left( \frac{\Delta(1-v)}{a} \right)^2 \right]^{-1} \quad (4.9)$$

Defining

$$\delta \equiv \frac{\Delta}{a} \quad (4.10)$$

$$\eta \equiv v - \frac{1}{2}$$

then (4.9) assumes the symmetrical form

$$\begin{aligned} g &= \left[ 1 + \delta^2 \left( \eta + \frac{1}{2} \right)^2 \right]^{-1} \left[ 1 + \delta^2 \left( \eta - \frac{1}{2} \right)^2 \right]^{-1} \\ &= \left[ 1 + 2\delta^2 \left( \eta^2 + \frac{1}{4} \right) + \delta^4 \left( \eta^2 - \frac{1}{4} \right)^2 \right]^{-1} \end{aligned} \quad (4.11)$$



Considering that the fault may lie somewhere between one of the outside wires and one of the inside wires we take our range of interest as

$$\begin{aligned} 0 &\leq x_1 \leq \Delta \\ 0 &\leq v \leq 1 \\ -\frac{1}{2} &\leq \eta \leq \frac{1}{2} \end{aligned} \quad (4.12)$$

Differentiating  $g$  with respect to  $\eta$  we find extrema of  $g$  at

$$\begin{aligned} \eta_1 &= 0 \\ \eta_2 &= \pm \left[ \frac{1}{4} - \delta^{-2} \right]^{1/2} \quad \text{if } \delta > 2 \text{ for } \eta \text{ real} \end{aligned} \quad (4.13)$$

at which

$$\begin{aligned} g_1 &= \left[ 1 + \left( \frac{\delta}{2} \right)^2 \right]^{-2} \\ g_2 &= \delta^{-2} \quad \text{if } \delta > 2 \end{aligned} \quad (4.14)$$

Now restricting  $\eta$  as in (4.12) we see that the  $\eta_2$  solution applies in our range of interest provided  $\delta > 2$ . Next, also take the extrema of our range of interest as

$$\eta_3 = \pm \frac{1}{2} \quad (4.15)$$

for which

$$g_3 = [1 + \delta^2]^{-1} \quad (4.16)$$

Then  $g_1$ ,  $g_2$  (for  $\delta > 2$ ), and  $g_3$  represent the range of variation of  $g$  over  $\eta$  in the range of interest. The closeness of these numbers represents the uniformity of being able to detect a fault with respect to position on the shield wall.

As an example suppose we wished the coupling between wires on one side of the shield wall to be about 1%, giving

$$f_o = .01$$

$$\delta = \frac{\Delta}{a} = 5 \quad (4.17)$$

Our corresponding uniformity numbers are

$$g_1 = .019$$

$$g_2 = .040$$

$$g_3 = .0385 \quad (4.18)$$

This represents a factor of 2 variation in the detection of the signal through the fault with respect to the location of the fault on the shield wall. This illustrates the trade off to be made in the design.

V. SUMMARY

This gives the general outline of the SCUTUM technique for characterizing and monitoring shield enclosures. It can be operated in CW or pulse mode, but pulse mode may be more convenient for fault location.

Our discussion has centered on aperture-like faults because of their practical importance. However, diffusion through metal walls is also picked up by this technique which can be considered a generalization of the technique in [6].

The present discussion has considered locating a single aperture (say at  $X, X'$ ). The technique, however, is more general and can locate multiple apertures by considering successive pulses that arrive at B, the first pulse that arrives being from the first aperture, etc. If the propagation speeds on the outer and inner transmission lines are (nearly) the same, the pulses from all the apertures arrive at B" at (nearly) the same time. The time difference of pulse arrival between B and B" can then be used to locate all apertures (if the number is not too large) excited by the transmission-line pair.

There are still various detailed problems to be considered. For example, seams at the edges of the faces of the shield enclosure have different geometries for electromagnetic coupling from the case considered here. There are also the details of the construction of the transmission lines and spacing them from other external and internal structures.

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