Sensor and Simulation Notes

Note 333

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Topology for Transmitting Low-Level Signals
from Ground Level to Antenna Excitation Position in Hybrid EMP Simulators

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Abstract

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electromagnetic pulse simulators, coaxial cables
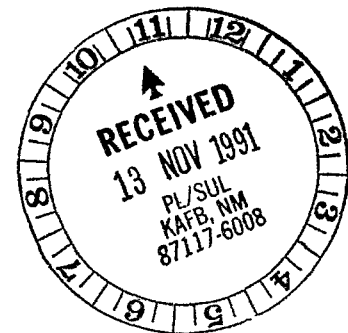
I.   Introduction

A hybrid EMP simulator [4,5], such as outlined in fig. 1.1, has three essential characteristics:

1.   The high-frequency (early-time) fields are radiated to the test volume from a (relatively) small source region (B) in the antenna structure.

2.   The antenna forms a loop for current to flow around the test object (including ground return, or image) giving a quasi-static magnetic field at the test object for low frequencies (late times). This loop includes resistive loading to give a quasi-static electric field as well, with R' (resistance per unit length) chosen so that the low-frequency E/H ratio is Z_0 ($\simeq 377\ \Omega$) in the case of a full loop (including image antenna with zero image source voltage), or $Z_0 \cos(\psi)$ including the earth reflection (for high ground conductivity).

3.   The antenna is slender so that at intermediate (as well as high) frequencies the energy is allowed to radiate away and not produce significant resonances.

Various detailed shapes of the loop are possible consistent with these three points. Figure 1.1 illustrates the case of an elliptical shape (ELLIPTICUS in the low-voltage resistively-loaded-wire case). Other shapes (e.g., rectangular and diamond (or rhombic)) are also possible, but note that the optimum resistive loading (point 2) is geometry dependent. For a toroidal shape (a canonical hybrid shape due to symmetry) the optimum resistive loading is found to be [3,5]

$$R' = \frac{1}{2\pi a} Z_0 \left\{ \ell n\left(\frac{8a}{b}\right) - 2 \right\}$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \equiv \text{wave impedance of free space } \simeq 377\,\Omega$$

(1.1)

$a =$ major radius of toroid

$b =$ effective minor radius (effective cage radius)

While this formula can be approximately applied to other loop shapes (non-circular), more detailed calculations [6] can give more accurate results, including the influence of source location. Note also that the shape also affects the intermediate-frequency performance (point 3).

In its traditional form there may be a high-voltage (multi MV) pulser at the source. This has significant weight requiring a strong mechanical structure (dielectric so as not to significantly distort the fields) for support. The power to the pulser can be in the form of high voltage (e.g., ±50 kV) through resistor strings (with resistance per unit length » R') inside the resistively loaded antenna cage
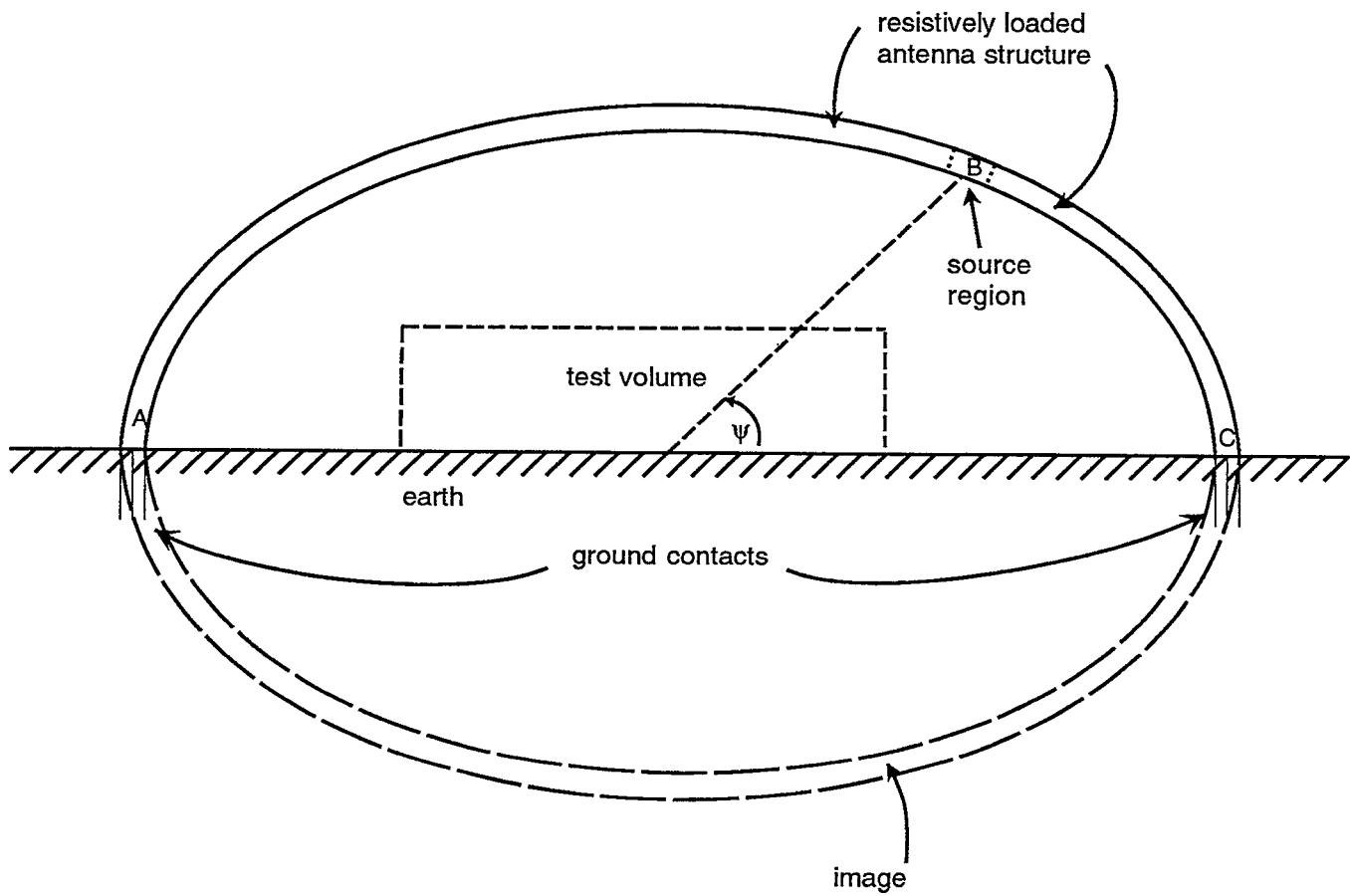
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Fig. 1.1. Hybrid EMP Simulator

structure forming the loop. Pneumatic controls and fiber optics telemetry and controls have also found use.

Suppose now that one wishes to use a CW source over some broad band of frequencies in place of the high voltage pulser. This might be at very low amplitude for use in measurement of transfer functions (perhaps including phase as well as magnitude) to various positions in the system under test. This can be done by replacing the pulser with a CW source in the same (large, say a few meters in diameter) wire-cage antenna, and using the existing mechanical support structure.

Recognizing that for CW transfer functions one needs only low-level fields, and that efficiency in the sense of kV/m per MV in the pulser is not a problem one can modify the design of the antenna. In particular the antenna need not be a wire cage; but could be a resistively loaded single wire with an equivalent diameter in the cm range. This will, in general, lower the weight of the antenna. Now if there were some way to lower the weight of the source up somewhere in the antenna structure, one could significantly reduce the strength required of the dielectric mechanical support for the antenna and source.

Suppose one were to have the source on the ground and transmit the signal via a high-quality coax cable up to the old source location, perhaps with some matching network there to drive the antenna. Then one is faced with the problem of how to route the coax from the ground up to the antenna feed position. Such a cable is a very large electromagnetic scatterer and, except under special symmetry conditions, will strongly perturb the fields produced in the test volume. Furthermore, the test volume itself needs to be far from this cable to avoid interaction with the test object.
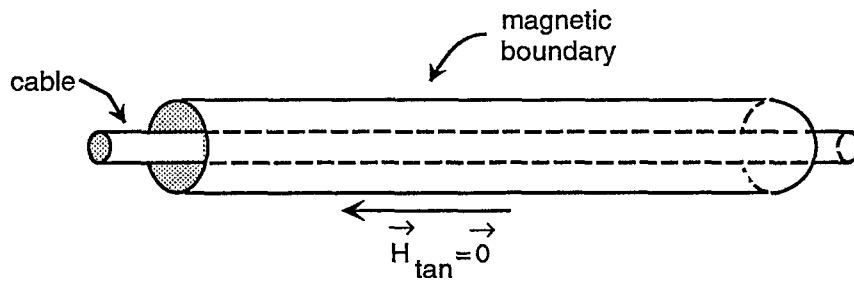
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II.   Making Long Slender Conductors Disappear

The problem with a long slender conductor (such as a coaxial cable shield) is that, if there is a component of an incident electric field parallel to the path of this conductor, then large axial currents are induced with associated large scattered fields. Incident electric-field components transverse to this path scatter relatively little, such scattering being related to the small transverse dimensions of the conductor.

One way to look at this is the asymmetry in the physical world seen in the presence of electrical conductors (e.g., metals), compared to the lack of magnetic conductors (due to the apparent lack of magnetic monopoles). One might consider an ideal magnetic boundary as in fig. 2.1A for its possible use in containing conductors (cables) inside a long slender magnetic tubular boundary. This isolates the interior cable from the external fields (no currents on the cable exterior). However, by forcing the external axial magnetic field to zero this kind of a "shield" is also a large scatterer of the external fields. This is just the dual (interchanging E and H) of a slender conductor. Of course, there is no such ideal magnetic conductor, but it can be approximated by a pipe with a high permeability (and thick) wall as in fig. 2.1B. This also shows part of the problem in such an approach in that a large axial magnetic flux is induced in the wall of such a pipe.

A way out of this problem of electric versus magnetic boundaries is to mix them, i.e., expose suitable short lengths of the conductor (cable shield) to the external incident electric field, while separating these by use of inductive magnetic cores (effective magnetic boundaries) as indicated in fig. 2.1C. Such cores represent a localized high impedance (a choke) limiting the current induced on the conductor. For sufficiently large impedances we can think of the exterior scattering as being from a colinear array of unconnected short conductors. This scattering will be small provided core spacing d is small compared to the half wavelength. Note also that the separation between cores breaks up any significant increase of magnetic flux parallel to the conductor. In the limit of a large number of separated cores we can think of a dielectric/magnetic sandwich comprised of alternate thin layers of magnetic material separated by thin dielectric layers as discussed in [9]. Here we are looking at such a structure from the exterior properties as compared to the interior emphasis in [9]. Even with separated cores as in fig. 2.1C , the individual cores might be constructed in such a sandwich form for high-frequency purposes.
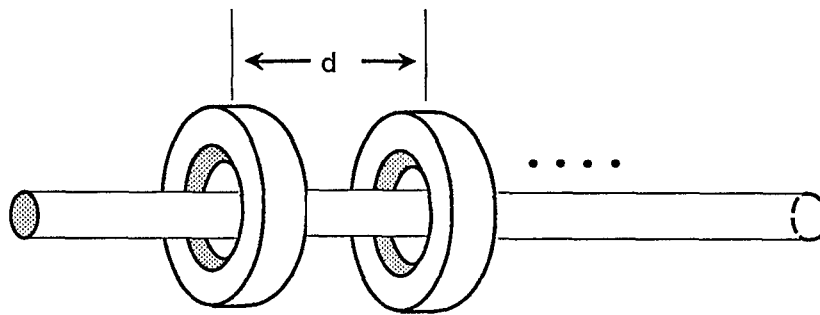
With this general concept of effectively isolating the conductor by the alternating electric/ magnetic boundaries for the exterior fields we can think of this in topological terms. This is analogous to a wormhole which conceptually returns electric flux lines (to make them closed) between positive and negative charges [10]. This wormhole is postulated to pass between the charges in some higher dimension of space. Another paper [8] shows how a special helical transmission line can propagate an

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A. Tubular magnetic boundary

$$\overleftarrow{\qquad}$$
$$\overrightarrow{H}_{tan} = \overrightarrow{0}$$

magnetic
boundary

cable
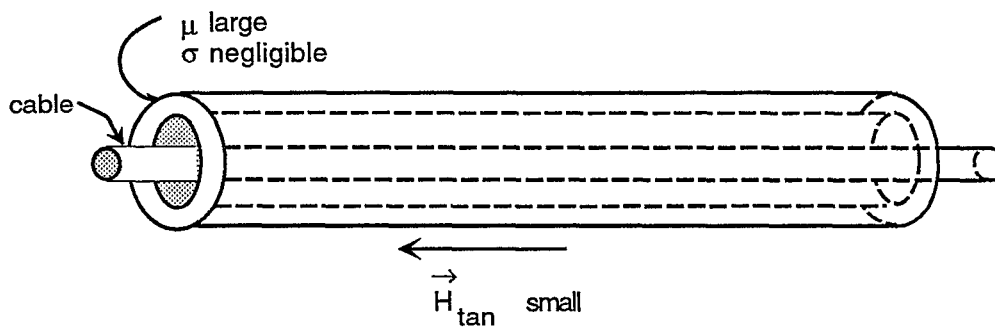
B. Pipe of high permeability

μ large
σ negligible

cable

$$\overleftarrow{\qquad}$$
$$\overrightarrow{H}_{tan} \text{ small}$$

C. Spaced inductive cores

d

· · · ·

Fig. 2.1. Progression from Magnetic Boundary to Spaced Inductive Cores

effective magnetic monopole with the magnetic field lines closing by returning through the tube formed by the helical solenoid. In the present case a well-designed alternating electric/magnetic boundary gives something like a wormhole, in the sense that a signal cable can pass between two points in three-dimensional space without being there (approximately) in an exterior electromagnetic scattering sense.

III.   Making Long Slender Conductors Have Prescribed Impedance Loading

Having a technique to approximately hide a conducting cable, the next question is where to place this cable path with its special "shield". Referring back to fig. 1.1 the topological problem is where to place this path with endpoints at B and somewhere on the earth surface. As mentioned previously, the path should be excluded from the test volume since the system under test is to go there. Furthermore, one would prefer that this path not be close to the test volume because its shield is as a practical matter imperfect (non completely invisible).

Observe that there are already two earth-contact positions, A and C, for the simulator proper (antenna). At these locations there are ground rods "already" in place. One could use either A or C, but since one of these may be closer to B (i.e., C in the fig. 1.1 example), we may choose this one and make our conductor path connect B and C. The next question concerns where the conductor path from C to B should be placed. An obvious choice is to place it along the same path as the resistively loaded antenna structure where it can be supported by the same dielectric support structure (poles, catenary, etc.).

Then, as in fig. 3.1A, consider that there is a current I along the antenna path consisting of wire-connected resistors, each of value

$$R = \frac{R'}{v}$$

$$v \equiv \text{ number of resistors per meter}$$

(3.1)

Let the adjacent cable path have its inductive cores (chokes) spaced the same as the resistors (v per meter) giving

$$d = \frac{1}{v}$$

(3.2)

and positioned adjacent to the resistors. With negligible current on the cable-shield exterior (for half wavelength $\lambda/2 \gg d$), let us electrically connect each wire between resistors to the corresponding adjacent position on the cable-shield exterior via the connection paths in fig. 3.1A. Negligible current runs on these connections. Then as in fig. 3.1B deform the wire and connections so that the current I passes through the resistor to the cable shield and back to the next resistor, etc. Negligible current still passes through each choke on the cable-shield exterior. Then in fig. 3.1C the wires connecting each resistor to the cable shield on opposite sides of a choke are slid together (inside the choke), connected to each other, and removed (not necessarily) from the cable shield. Now I flows on the cable-shield exterior
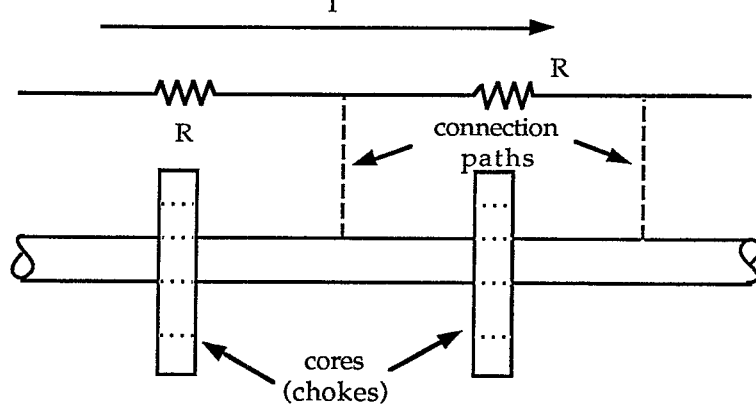
A. Resistively-loaded wire in parallel with core-loaded cable
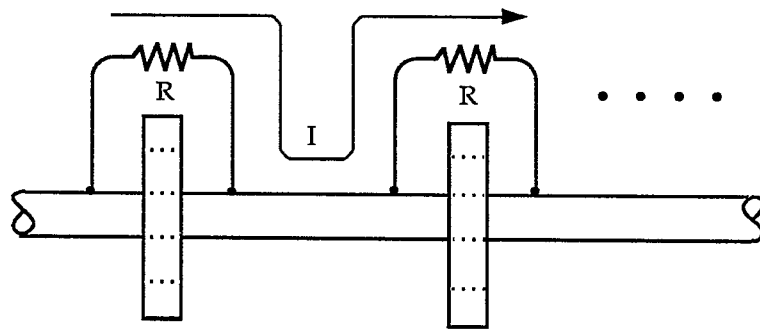
B. Current diverted to cable-shield exterior
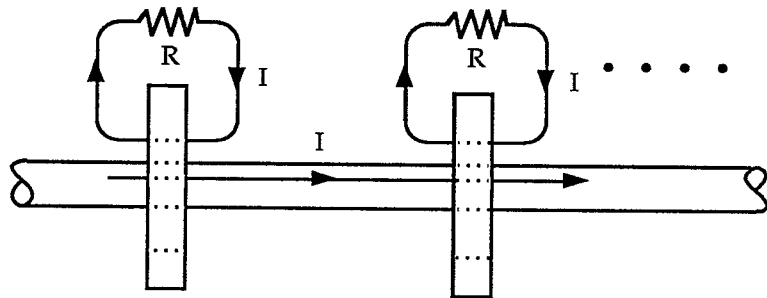
C. Current through resistors separated from opposite current on cable-shield exterior

Fig. 3.1. Progression from Adjacent Paths to Common Path for Resistively-Loaded Cable-Shield Exterior

through the choke but is cancelled by an opposite I on the wire connected (both ends) to the resistor. The choke now acts as a transformer.

The two paths have now become one. There is a significant, but controlled, current I on the cable-shield exterior. The cable shield should be a good one, say a continuous metal tube (aluminum or copper) instead of a braid. This is consistent with a high-quality foam-dielectric (or similar) coaxial cable capable of efficiently transmitting signals in the GHz range. The requirement to make the cable "invisible" by the special alternating electric/magnetic boundary has been made a little easier. It need not prevent "all" current from flowing on the cable-shield exterior, but merely limit it to I, the value desired for the antenna.

Figure 3.2A shows a view along the cable axis of the core and loading resistor (with wire linking through the core). The current I (approximately) in this wire associated with the resistor is not centered in the core, giving a nonuniform excitation of the core. One can compensate by offsetting the cable shield to obtain better angular uniformity for the magnetic field associated with the common mode (small) of the currents on this wire plus cable-shield exterior. Better one can replace the single resistor of resistance R by N resistors, each of resistance NR spaced at equally angles ($2\pi/N$) around the core as indicated in fig. 3.2B. This gives a more uniform current and magnetic-field distribution in an angular sense around the core. One can extend this concept by replacing the wire loops by a continuous metal structure with a circumferential slot around the outside [1,2], the N resistors being connected across this slot.

If the core is approximated as a simple inductance L, then define
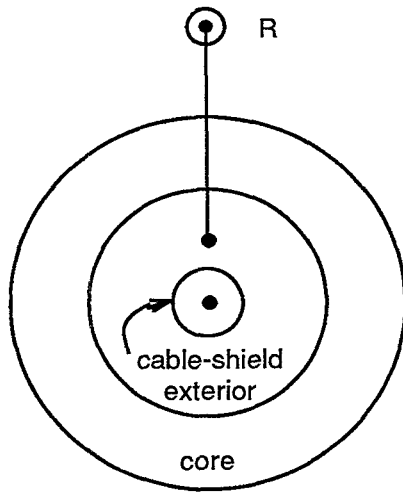
$$\omega_o \equiv \frac{R}{L}$$

(3.3)

The effective impedance of the resistor-loaded cores is then

$$\tilde{Z}(s) = R \,/\!/\, (sL) = \left[\frac{1}{R} + \frac{1}{sL} \right]^{-1}$$
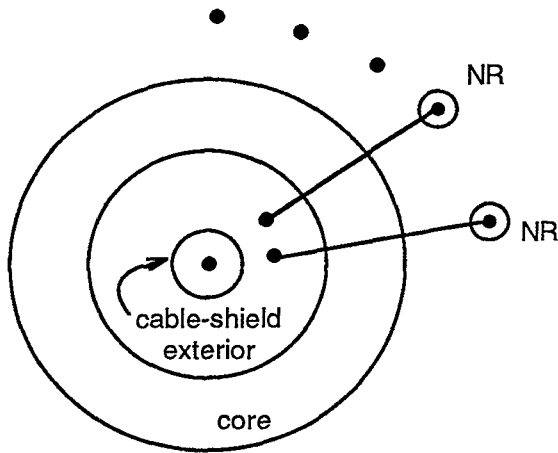
(3.4)

$s = \Omega + j\omega \equiv$ Laplace - transform variable or complex frequency

In this form the resistor-loaded cores give an effective impedance per unit length R' for this antenna/cable path provided

$$\omega_o \ll \omega$$

(3.5)

A. Single resistor

B. Multiple (N) resistors in parallel

Fig. 3.2. Resistively Loaded Cores

For a given R' then one can choose v (= 1/d) and L to make ω_0 some desired low-frequency limit on the ideal performance of the antenna.

In a more general sense the choke impedance $\tilde{Z}_{ch}(s)$ need not exactly follow an inductive form sL for L constant (>0). In this more general case we have

$$\tilde{Z}(s) = R \,//\, \tilde{Z}_{ch}(s) = \left[\frac{1}{R} + \frac{1}{\tilde{Z}_{ch}(s)} \right]^{-1} \tag{3.6}$$

For R' to dominate the antenna performance we require

$$\left| \tilde{Z}_{ch}(j\omega) \right| \gg R \tag{3.7}$$

for frequencies of interest, so it is important only that the choke impedance be large compared to R. As one increases the number of resistors (decreasing d) R is decreased, making the requirement of (3.7) be met for a broader band of frequencies.

IV. Inclusion in Hybrid Simulator

Referring back to fig. 1.1 we now have the simulator geometry and impedance loading in its desired form without extraneous conductors around to distort the fields and interact with the test object. This includes the absence of conductors along the ground surface since these also distort the current density in the ground and associated fields. In particular there should be no conductors (such as for power) leading to C where the signal source is located, or between any combination of A, C, and the test object. Reference signals from C to the test object, field sensors, etc., can be telemetered by modulation of the information on a carrier with frequencies outside the range of the measurements (e.g., on fiber optics).

At B, where the signal is introduced onto the antenna, there is a matching problem. If the coaxial cable from C to B is 50 Ω, this is considerably different from the input impedance of the antenna which ranges from a few hundred ohms at high frequencies ($\lambda \ll a$) to kilohms at low frequency ($\lambda \gg a$) [6]. This can be accomplished by introducing some kind of matching network at B (signal exit from coax) as indicated in fig. 4.1. This might be as simple as a resistor of a little more than 50 Ω from center conductor to shield with center conductor connecting across to the conductor on the other side of the feed (which might be the shield of another identical coax with unused center conductor). The antenna input impedance in parallel with the loading resistor should give approximately the characteristic impedance of the coax (say 50 Ω). Alternately one can accept the mismatch at the antenna feed provided the CW source at C has a source impedance matched to the cable characteristic impedance. Another approach that is efficient in a power sense has a balun at B to raise the coax impedance closer to the antenna impedance (say 50 Ω to 200 Ω), perhaps used in combination with some resistive loading.

In the vicinity of B special considerations can also be applied to the shaping of the antenna conductors, for example by preferentially propagating the fields toward the test object [7]. As indicated in fig. 4.1 one should not overly narrow the antenna pattern at high frequencies since it has to approximately uniformly cover the test volume (fig. 1.1). Noting, however, that there is some loss in the GHz regime for signals propagating on high quality (solid conductor) coaxial cables, a modest high-frequency improvement could help compensate for this loss. Note also that one need not place the resistively-loaded chokes too close to the antenna feed (since they reduce the antenna currents) and gain some further high-frequency improvement. In addition one can start the chokes with small resistances (and more per unit length), and perhaps taper from smaller R' values to minimize the discontinuity encountered by the current wave. From a high-frequency point of view the most severe requirements are on the resistivly-loaded chokes in this region. If the coaxial cable has an outer dielectric covering one may wish to remove it near the feed region so that a slow-wave condition is not produced on the cable shield.
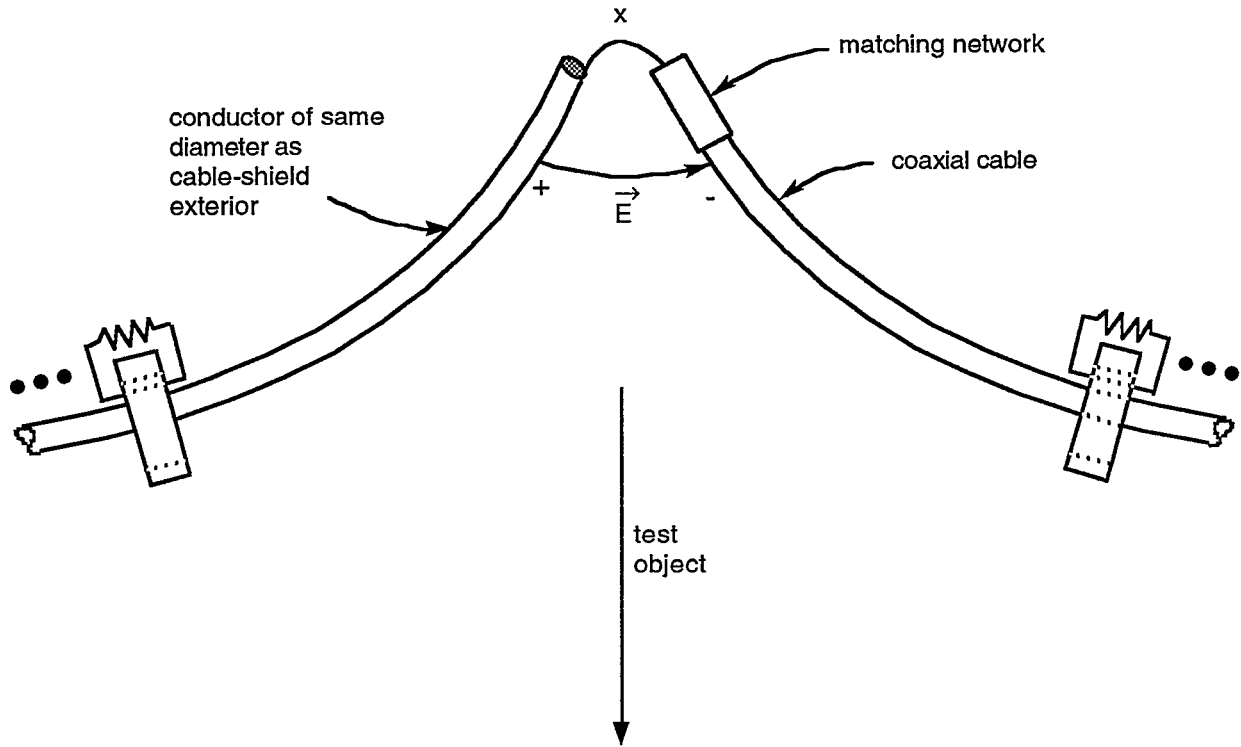
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conductor of same
diameter as
cable-shield
exterior

matching network

coaxial cable

x

+

$\vec{E}$

-

test
object

Fig. 4.1. Matching Network at Antenna Feed

V. Concluding Remarks

So, for low-level drive of a hybrid EMP simulator, one can make the antenna in a way which gives a sparse (and relatively lower weight) antenna. The low-level source (CW or pulse) is moved to one of the antenna connection points to the earth, and the signal is fed up to the antenna feed position via a high quality coaxial cable. Resistively loaded chokes are used to control the current on the cable-shield exterior, thereby making the cable part of the antenna.

There are limitations in the practical realization of this technique. The choke impedance has to dominate the loading R for frequencies of interest. Since the choke is an inductance for low frequencies, the inductance must be sufficiently large to obtain the desired performance at low frequencies of interest. At high frequencies the cable needs to be of sufficiently low loss for the length needed. Furthermore, there should be a sufficiently small spacing d between chokes so that there are not significant resonances on the cable shield exterior. This last point may be improved by introducing some variation (perhaps random) in the spacing between successive resistively loaded chokes.

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