Interaction Notes

Note 503

24 May 1994

Damping Transmission-Line and Cavity Resonances

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ABSTRACT

In the interaction of electromagnetic fields with complex electronic systems there are often low-loss resonances associated with conductors (transmission-line modes) and cavities. These resonances can allow the effective transmission of undesirable signals through the systems at the resonance frequencies. This paper discusses techniques for suppressing (damping) such resonances. These involve various spatial distributions of resistors (in some cases with inductors (chokes)).

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I. Introduction

The interaction of electromagnetic (EM) fields with complex electronic systems is a very complex process, typically involving many poles (or complex resonances) in the complex frequency (or $s = \Omega + j\omega$) plane. These include exterior resonances (say on an airframe) as well as interior resonances involving various equipment, cabling, and cavities. This complicated interaction problem is considered in detail in [12].

As discussed in [5, 9] the phenomenon of resonances is quite important in the interaction process. If the incident external electromagnetic environment is approximately CW in nature with some dominant frequency f_s, then tuning f_s to one of these resonances greatly increases the system response, say by an order of magnitude or so. Here, the system response is considered as the voltage V_i (or current) at some interior "failure port" of interest (e.g. a pin in a connector into some equipment box). This increased system response applies also to a pulsed CW signal as long as the pulse width is large enough to "ring up" the response signal. Basically this pulse width should be at least as large as the decay time $-1/\mathrm{Re}[s_\alpha]$ of the complex resonance s_α of interest. Then the resulting transient signal will have a maximized peak value (∞-norm), as well as a large 2-norm which can be further increased by additional increase of the incident pulse width.

In designing a system with electromagnetic protection, the concept of electromagnetic topology is quite important [11]. By dividing the system into layers/sublayers (volumes) separated by shields/subshields (surfaces), one can use these boundary surfaces to control the penetration of electromagnetic signals into the system. Looking at some individual volume in the system let us consider it as some generalized cavity problem. This cavity can often be considered as having perfectly conducting walls which form closed boundary surfaces, except for some penetrations: apertures and conductors (passing through apertures). The conductive penetrations can be closed to varying degrees by electrical connection to the cavity walls, and for conductors carrying electrical signals by use of filters and limiters [8, 10]. The apertures can be made smaller or covered (e.g. as hatches) in some cases. In any event these techniques are not in general perfect and some electromagnetic fields enter the cavity.

Inside the cavity there is in general an assortment of conducting cables (shielded or unshielded wires) connecting to (or through) the walls and perhaps terminating at electronic boxes inside the cavity. The electromagnetic fields inside such a complex structure are quite difficult to describe with any precision. A simplified view has a set of natural modes divided into two kinds. There are transmission-line modes (quasi-TEM) associated with the cables, and cavity modes appropriate more to the empty volume away from the cables. The transmission-line modes tend to be more important at lower frequencies, while the cavity modes tend to be more important at higher frequencies. This approximate division is useful for considering techniques for suppressing (damping) these resonances.

One can obtain an approximate solution to the BLT equation (describing signal propagation on the EM topology) known as the good-shielding approximation [6, 7, 11]. Here the supermatrix equation is reduced to a form in which the various blocks of the interaction supermatrix appear in a product corresponding to the successive propagation of signals through shields and layers (surfaces and volumes). The volume matrices are inverted, so it is important that these matrices are not nearly singular. The resonances in the volumes need to be damped to make these matrices less singular, and thereby make the good-shielding approximation more valid. Thinking of this another way, undamped resonances allow unattenuated signal propagation through the volume (from one penetration to another) at the associated frequencies.

II. Conductors Passing Through Cavities

Our first canonical damping problem concerns the transmission-line (quasi-TEM) propagation on conductors inside the cavity. As in fig. 2.1 let there be some conductor (a cable shield, fluid pipe, etc.) passing through the cavity, or at least connected to the cavity walls at two (end) positions. For simplicity let the conductor be parallel to some of the walls so that we can characterize propagation of voltages and currents on this conductor by a characteristic impedance Z_c with respect to the appropriate walls. As indicated in fig. 2.1A this conductor is electrically bonded to cavity walls as it passes through the cavity walls to stop (or severely impede) EM waves from passing through this penetration (say from one cavity to the next). The resulting conductor of length ℓ then has resonances at frequencies such that ℓ is an integer number of half wavelengths. These are excited by fields penetrating at some other penetration (conductive or aperture) into the cavity. At resonance the currents on this conductor can be very large and some kind of loading can be used to significantly reduce these currents.

One approach to suppressing the resonances is indicated in fig. 2.1B by series terminating impedances at the cavity walls. If we choose a resistance R_1 with

$$
\begin{aligned}
R_1 &= Z_c = \left[\frac{L'}{C'}\right]^{\frac{1}{2}} \\
L' &\equiv \text{inductance per unit length} \\
C' &\equiv \text{capacitance per unit length}
\end{aligned}
\tag{2.1}
$$

then all transmission-line waves are terminated (no reflections) at the walls. In a transient sense currents on the conductor are terminated (cease) in one transit or less of the conductor depending on the effective source location on the conductor. In order to realize this termination one might have N parallel resistors, each of resistance NR_1 in parallel with an inductance L_1 with

$$
\begin{aligned}
\frac{L_1}{R_1} &\gg \frac{\ell}{c} = \text{transit time of conductor} \\
c &\equiv [\mu_o \, \epsilon_o]^{-\frac{1}{2}} = \text{speed of light (or speed of propagation in medium if other than free space)}
\end{aligned}
\tag{2.2}
$$

A limitation of this technique is then associated with the impedance of the choke (ideally sL_1). Typical values for Z_c are around a hundred ohms, and it may be difficult to make chokes with impedances larger than this in the hundred MHz to GHz range.

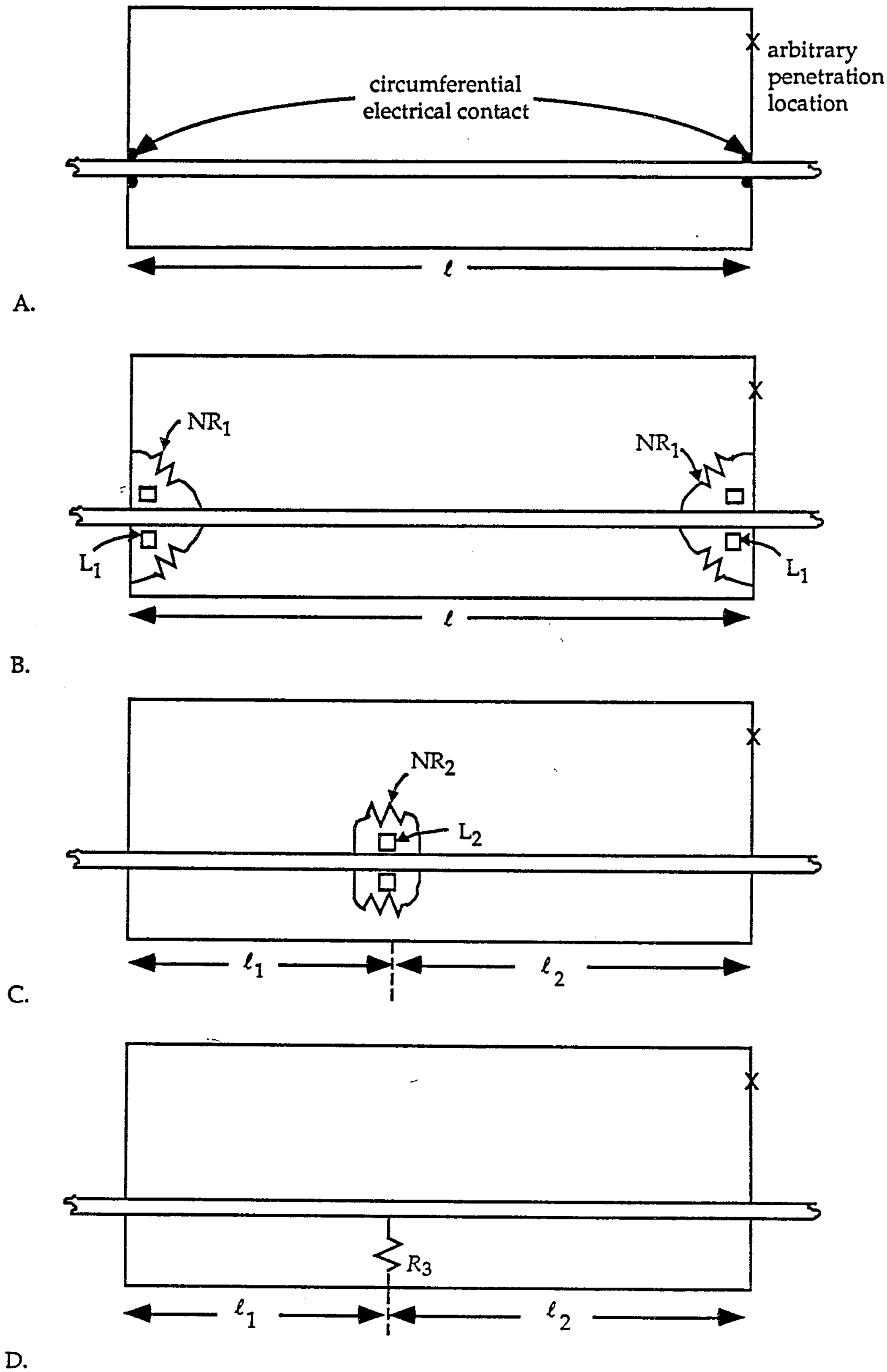


Figure 2.1 Loading Conductor in Cavity

An alternate arrangement is to place the series loading of the conductor somewhere between the two walls as indicated in fig. 2.1C. Assuming that the inductance L_2 is sufficiently large, the N resistors of resistance NR_2 in parallel give a series resistance of R_2 in the conductor. There are various ways to choose R_2 in some optimal sense. A simple view is to consider the conductor length ℓ as infinitely large and have a transmission-line wave incident from one side. The resistance removes the maximum energy when the sum of the squares of the transmission and reflection coefficients is minimized, or the product of the current squared times R_2 in the resistor is maximized. This is a similar calculation to that done for uniform plane waves in [4]. So set

$$\frac{d}{dR_2}\left[R_2\left[\frac{2\,Z_c}{R_2+2\,Z_c}\right]^2\right] = 0$$
$$\frac{2\,Z_c}{R_2+2\,Z_c} \equiv \text{transmission coefficient} \tag{2.3}$$

from which we find

$$R_2 = 2\,Z_c \tag{2.4}$$

as an optimal choice with transmission and reflection coefficients both 1/2. Half the incident power is absorbed by R_2. Here we still have the problem of making the impedance sL_2 sufficiently large at the frequencies of interest.

Including the distances to the walls ℓ_1 and ℓ_2 with

$$\ell_1 + \ell_2 = \ell \tag{2.5}$$

the choice of R_2 is not so simple, and one needs to consider where to put it. With the wall connections as current maxima then

$$\ell = m\frac{\lambda}{2}\ ,\ m = 1,2,... \tag{2.6}$$

corresponds to the line resonances. The location of R_2 should not be at a current minimum for any important resonance. Practically speaking ℓ_1/ℓ should not be a ratio of small integers so that the lowest order modes all have some damping.

Another technique with a shunt resistance R_3 is indicated in fig. 2.1D. This has the advantage that a choke is not needed in parallel with the resistance. Now for an infinite transmission line with a voltage wave incident from one side, the power absorbed by R_3 is the voltage squared divided by R_3. So set

$$\frac{d}{dR_3}\left[\frac{1}{R_3}\left[\frac{2\,R_3}{2\,R_3+Z_c}\right]^2\right] = 0$$

$$\frac{2\,R_3}{2\,R_3+Z_c} \equiv \text{transmission coefficient} \tag{2.7}$$

from which we find

$$R_3 = \frac{Z_c}{2} \tag{2.8}$$

as an optimal choice, again with transmission and reflection coefficients both 1/2. Half the incident power is absorbed by R3. Concerning the location of R3 for the case of finite ℓ, this should not be at a voltage minimum for the modes in (2.6). Again this implies that ℓ_1/ℓ, should not be the ratio of small integers.

In the case of the series and parallel resistors in figs. 2.1C and 2.1D, we need not be limited to one load position. Various distributions of multiple loads are possible. Of course, one should not place these resistors so that at some frequencies they are all at current or voltage minima respectively of the modes given by (2.6). One might even space the loads with a random or log-periodic distribution so as to better dampen all the modes of concern. One can even combine both kinds of loads (series and parallel). As the number of loads becomes large it may be more useful to consider this as a case of continuous loading for which the transmission-line mode is characterized by

$$\gamma = \left[\left(sL' + R_s'\right)\left(sC' + G_p'\right)\right]^{\frac{1}{2}}$$

$$\equiv \text{propagation constant}$$

$$Z_c = \left[\frac{sL' + R_s'}{sC' + G_p'}\right]^{\frac{1}{2}} \equiv \text{characteristic impedance}$$

$$R_s' \equiv \text{series resistance per unit length} \tag{2.9}$$

$$G_p' \equiv \text{parallel conductance per unit length}$$

With waves propagating as $e^{\pm \gamma z}$ (with z as the coordinate along the transmission line) the problem is then transformed to one of attenuating all frequencies of interest by a significant factor in one transit along the transmission line (length ℓ).

III. Cavity Modes

Even with no conductors passing through the cavities there can be low-loss resonances which can allow passage of electromagnetic energy through the cavity (from one penetration to another or to some equipment in the cavity) at the resonance frequencies. These resonant modes are well understood in the canonical separable geometries (sphere, circular cylinder with flat end caps (perpendicular to the axis), and rectangular parallelepiped). Such modes also exist in arbitrarily shaped closed volumes with (approximately) perfectly conducting boundaries.

One way to dampen these modes is to place discrete loads with appropriate coupling antennas (electric and magnetic) at the cavity walls as discussed in [1]. This has the problem of inefficient coupling to the cavity modes (and hence small damping) for electrically small loading antennas. For damping many modes one also needs such loading antennas at many locations on the cavity walls to avoid null locations of the various modes. One can extend this to an impedance loaded liner inside the cavity, preferably in contact with the cavity walls, involving a lattice of resistors carrying currents parallel (two directions) and perpendicular to the nearby wall [1, 3]. This has the advantage of leaving the central portion of the cavity empty, but limits the damping attainable depending on how thick one is willing to make the liner. This is discussed in detail in [1, 2] for the case of a spherical liner, and will not be repeated here.

In the present paper let us consider the simpler case of a damping grid of resistors distributed throughout the cavity. In a manner similar to Section II consider the fields as plane waves (now uniform as well as TEM). As discussed in [4] a single resistive sheet of sheet resistance R_s can be used to attenuate (and reflect) an incident plane wave. With α as the angle between the direction of incidence and the planar sheet, an E (or TM) wave has the optimal choice for R_s as

$$R_s = \frac{Z_0 \sin(\alpha)}{2} \tag{3.1}$$

in which case the sheet absorbs half the incident power (just like in Section II). For an H (or TE) wave the optimal choice for R_s is

$$R_s = \frac{Z_0}{2 \sin(\alpha)} \tag{3.2}$$

with again half the incident power absorbed. If we consider the special case of normal incidence we have

$$\begin{aligned} \alpha &= \frac{\pi}{2} \\ R_s &= \frac{Z_o}{2} \end{aligned} \tag{3.3}$$

which directly corresponds to the case of shunt loading of the transmission line as in (2.8). Noting that a general plane wave may have both polarization components and may be coming at any angle of incidence, then the case in (3.3) may be considered a reasonable compromise.

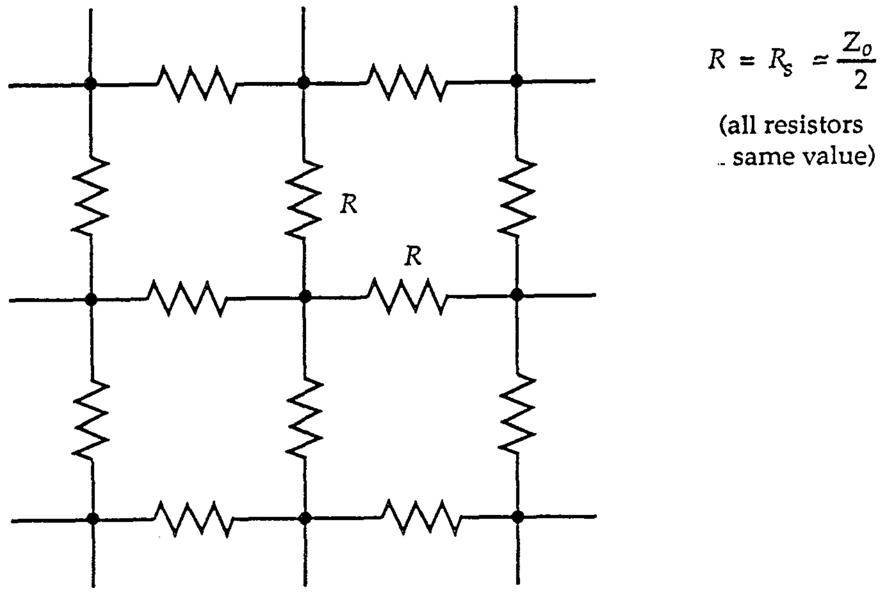
In realizing such an impedance sheet one can use an array of resistors as in fig. 3.1A. Here a square pattern is used so that currents are conducted in both directions on the sheet and each resistor has a value R equal to R_S. Other patterns such as those based on equilateral triangles or regular hexagons can also be used to divide the planar surface on a periodic basis.

As in the transmission-line case one can have multiple sheets, which raises the issue of sheet spacing relative to nulls in the electric field of a resonant mode (analogous to (2.6)). Again a random or log-periodic spacing could be used. More importantly, since the wave can be considered as traveling in any direction, it can be traveling parallel to the sheets with no attenuation if the electric field is perpendicular to the sheets. So a more appropriate configuration is a three dimensional grid of resistors, as shown in fig. 3.1B for a lattice based on the edges of a cube. Other unit-cell shapes are possible, based on the symmetry groups such as used for crystal lattices. For example, instead of six resistors meeting at a cube corner one might have other orders of junctions based on cube diagonals (eight joining in cube center and eight joining at cube corners (vertices)). Other shapes involving tetrahedrons and octahedrons can also be considered. Again, however, one may wish to break up the periodicity by non-uniform spacings so as to avoid resonant modes with nulls at the resistors.

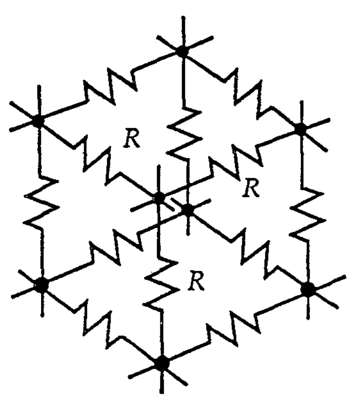
As the resistor lattice is made more dense (closer spacing) one can think of the damper as one with a volume conductivity σ, in which case the electromagnetic wave is characterized by

$$\begin{aligned} \gamma &= \left[s\mu_0(s\epsilon_0+\sigma)\right]^{\frac{1}{2}} \equiv \text{propagation constant} \\ Z &= \left[\frac{s\mu_0}{s\epsilon_0+\sigma}\right]^{\frac{1}{2}} \equiv \text{wave impedance} \end{aligned} \tag{3.4}$$

Here the conductivity takes the role of G_p' in (2.9), but R_S is absent (unless μ_0 is replaced by a magnetic material with appropriate loss in $\tilde{\mu}(s)$). The above parameters are now chosen so that there is sufficient attenuation (say one or more e-folds) in transit in any direction across the cavity.



A. Single sheet



B. Three-dimensional array

Figure. 3.1 Resistor Array for Suppressing Cavity Modes

IV. Concluding Remarks

As we have seen there are various possible types of canonical damping structures for removing unwanted oscillations. Some techniques will be easier to implement than others depending on application, cost, weight, size, etc. While transmission-line modes and cavity modes have been addressed separately, one can see that the damping techniques are very similar. Furthermore, this division of mode types is an idealization for conceptual simplification. One can integrate the techniques into what might be called a hybrid damper. In this case a transmission-line conductor might replace a string of resistors running through the lattice in fig. 3.1B. One could also include LR loading as in fig. 2.1C on this conductor if desired.

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