ON THE EQUIVALENCE OF RADIATED AND INJECTED TESTS

by Prof. J. Perini
Syracuse University

Abstract

In a previous paper [1] the conditions under which radiated and injected tests were derived under solid theoretical grounds. In a subsequent paper [2] the results of paper [1] were validated, with the aid of numerical simulation, for the case of plane wave illumination. In this paper, the same numerical simulation is used to validate the results for illumination by a dipole. This is a more realistic situation since, specially for the low frequencies, the EUT is in the near field of the illuminating antenna. The conclusions are still the same.

Introduction

The application of radiated tests requires the generation and radiation of high field intensities. For environmental and security reasons, it is necessary that radiated tests be performed in shielded rooms or anechoic chambers. The financial investment required for these facilities and the associated high field intensity equipment required is very costly, and is an important consideration to potential testers. These problems have led to the suggestion of replacing radiated with injected tests. The idea that, the effects of a radiated test could be emulated by directly injecting much lower level voltages or currents at strategically selected points in the equipment under test (EUT), is very appealing. Low level injection testing requires less expensive generation equipment and may not require the use of shielded rooms or anechoic chambers. Therefore, the cost of injected test could potentially be much lower than radiated test.

In as much as this idea is intellectually satisfying, a fundamental question remains to be answered: under what conditions are the results of these two tests equivalent?

Formulation of the Problem

In previous papers [1,2], the theory of the equivalence of these tests was developed and discussed in detail. As a result of [1,2] the following assumptions must be made. The first, and most fundamental, was that the EUT should behave as a linear reciprocal network. The second was that several ports had to be specified in terms of placement of the injection sources establishing equivalency. These ports are usually terminated into loads, where voltages or currents are of interest, since they may be at the input of low level amplifiers or low voltage level integrated circuits. Sometimes the test requirement is to look for some visual effect on the EUT. An example of such a test is the susceptibility of TV receivers, as specified by CISPER, where an interfering pattern may show up on the screen. In such cases perhaps the input of the display device, or the video amplifier that drives it, could be used as ports.

Once the ports are decided upon it was shown that the correct injection sources are the equivalent Thevenin open circuit voltages or the equivalent Norton short circuit currents at the specified ports. They are measured or calculated for an arbitrary incident field level, say 1 V/m, at some specified location of the EUT. The theory showed that this field level has to be established at the EUT location with the EUT removed. It was also shown that the Thevenin equivalent impedances, or the Norton equivalent admittances, are automatically provided by the presence of the EUT at each port. Another very important conclusion was that all the injection sources have to be coherent, that is, they have to be derived from a single generator. They not only have to have the same frequency, and amplitude, but also have to bear the correct phase relationships among themselves at all times. Using all these assumptions, it was shown that the voltages and currents on the port loads are guaranteed to be the same for both tests.

It was also pointed out in [1,2] that nothing can be said about the relationship between the currents and voltages, of both tests, everywhere else in the EUT. In fact, there is no reason to expect that they even resemble each other since the two tests are not the same from an electromagnetic point of view. This leads to the important conclusion that the two tests cannot be made equivalent throughout the EUT. The best one can hope for is the equivalence at the ports. This fact has important ramifications as will be discussed later.

Simulation of Radiated and Injected Tests.

In order to verify the results discussed in the previous section, a very simple EUT, consisting of a three-conductor 2m long flat ribbon computer cable, will be used in the simulation. Instead of illuminating the EUT with a plane wave, as was done in the previous work, a more realistic approach was used. For all frequencies used, the illuminator is a dipole placed 3m away from the EUT and skewed 45 degrees in relation to the cable. The geometry is shown in Fig.1. For the higher frequencies the illuminator is a half wave dipole. For the lower frequency it is just a short dipole, as will be discussed later.

![Geometry of the Cable Simulation](image)

This simple EUT was chosen because it is easily and reliably modeled by available numerical techniques. It allows a convenient numerical validation of the theoretical conclusions developed in [1,2].

For all frequencies used in the simulation, the EUT is in the near field of the illuminating dipole. This was another reason to choose the dipole illumination rather than the plane wave. Since in the theory no a priori hypothesis were made about the illumination, the equivalence at the ports should still be true in this case. However the currents in the remainder of the EUT are expected to change with the type of illumination.

The EUT contains four ports which are terminated with four arbitrary resistive loads of 500, 228, 50, and 1000 ohms respectively.
The value of 228 was chosen since it is the characteristic impedance of two adjacent wires of the flat ribbon cable. The others were chosen to have loads similar, well below, and well above the characteristic impedance of the cable. The dielectric material of the flat ribbon cable is not included in the simulation since it has no effect on the validations sought in this paper. From Fig.1 it is clear that the middle wire is used as a return (ground) for the four ports. However if common and differential mode currents exist the numerical simulation will account for both of them.

Simulated Results

The simulation was carried out with the help of numerical computation using the well known Method of Moments (MOM) routine [3]. In this technique the total wire current is assumed to be concentrated in the wire axis. The current along each wire is then divided in small segments. Each segment has, over its length, a rectangular pulse of current with unknown amplitude. These amplitudes are then determined by numerically imposing the boundary condition that the total tangential E-Field, on the surface of the wires, is zero. The program output of interest is the value of each current pulse, in amplitude and phase, along the wire segments. It is a stair case approximation of the exact current. These segments are numbered continuously along each wire, extending to the next wire, until all wires are included. The MOM program used allows the placement of loads and voltage sources at any segment of the model. The MOM code has been known to yield extremely accurate results, especially for the configuration used here. The comparison to measured results is usually within a fraction of a dB.

In order to understand the graphs in the simulated results it is important to understand how the wires, segments, and ports are specified and numbered. In Fig.1 each wire is referred to as W1 through W8 respectively. Wire W8 is the illuminating dipole antenna. W1, W3, W5 and W7 are the wires where the ports are located. W2, W4, and W6 are the 2m cable wires. Next to each wire name there is a number in parenthesis. This number indicates how many segments are used in its MOM simulation. For example, W2(25) designates that wire W2 is divided up into 25 segments. The segment numbering starts at wire W1 and continues consecutively through wires W2, W3, ..., W8. Therefore the ports are located at segments 1, 27, 53 and 79 respectively.

The wire segments number is the abscissa of every simulation plot (Fig.2). Each plot is composed of three graphs. The graphs designated as "Radiated" and "Injected" represent the currents, in dBma or dBua, for the respective tests. The graph denoted as "Diff.R-I" is the difference, in dB, between the currents generated in the cable wires, and ports, by the radiated and injected tests respectively. This last plot is very important since it indicates, visually, how the currents induced by both tests differ from each other.

During the simulation, the radiated test is performed by placing the four loads at the four ports, and a voltage generator of 1 Volt at the center of the dipole. The currents are then calculated in all wires and ports. Next the open circuit voltages are determined by placing four large resistors of .1E+20 ohms at each port, and feeding again the dipole with 1V. The open circuit voltages are computed by multiplying the currents at the each port segment by the .1E+20 Ohm resistors. Finally the injected test is performed by placing, at each port segment, the respective open circuit voltage in series with the corresponding load, as described in [1,2]. The results of the injected and radiated tests, if equivalent, should generate the same current, in amplitude and phase, at each of the four ports.

Note that for the injected test the dipole is not needed. The question regarding the dipole is then: should it be left open, shorted or should it be removed? Simulations with these three conditions were performed. The change in the wire currents was practically non-existent. For the runs presented here the dipole was left in position with its input shorted.

Fig.2 shows the wire currents for the radiated and injected tests for a frequency of 300 MHz and the wavelength is 1m. The excitation dipole is now .5m long, or half a wavelength. Since the cable is two wavelengths long, the currents for both tests show a typical standing wave pattern. However, the detail behavior of each of these standing waves is quite different as far as the location, number and magnitude of the various maxima and minima are concerned. The graph "Diff.R-I" illustrates this very clearly. It is interesting to observe that the radiated test induces higher currents on the wires than does the injected test. It is important to point out that, once the "correct" open circuit voltages are applied, if the loads are changed, in both tests, to any other arbitrary values, the currents are still the same, for both tests, at the designated ports. The loads have no influence on the "value" of the open circuit voltages since the ports are left open during their "measurement." They only depend on the geometry of the EUT.

Fig.3 shows what would happen if the phases of the open circuit voltages were disregarded. Here only the "correct" magnitudes are used. Note that the port currents differ substantially from each other, as much as 18 dB at port 2 (segment 27). This shows that, in a multiport injection test, the injected sources must possess not only the correct amplitude but also the correct phase. In other words, the injected sources are required to be coherent. A common technique employed to inject currents on cables is through the use of a current transformer. The phases and amplitudes of the injected currents in each cable wire cannot be controlled individually since they depend only on the relative position of the current transformer and the cable, and the cable geometry. Therefore, a good correlation between the two tests should not be expected.

Fig.4 is similar to Fig.2 except that the frequency is now 100 MHz and the wavelength is 3m. The excitation dipole is 1.5m long, half wavelength. Again, if the "correct" injection sources are used, both tests are equivalent as far as the ports are concerned. Everywhere else the currents differ substantially in both tests, by as much as 28 dB. Note that now the line is only 2/3 of wavelength long. As expected the currents standing wave patterns have fewer oscillations, but still are quite different in the number, location and magnitude of the maxima and minima. Again the radiated test induces larger currents in the EUT.

Fig.5 shows the case where the frequency is now 10 MHz and the wavelength is 30m. The excitation dipole is now 2m long, just a short dipole. Note that, since the line is only about 1/15th of wavelength long, the currents on both tests cannot be expected to change much over the length of the line. Even so the equivalence is only valid at the four ports. The maximum current difference is about 6 dB. For this frequency it is no longer true that the Radiated test excites larger currents than the Injected test. The currents are plotted in dBua instead of dBma as in the other plots. The reason for such a small current is that the dipole is very short and is an inefficient radiator.

Simulations for frequencies below 10 MHz and above 300 MHz were also carried out and the results did not change much: they exhibited large differences between the currents for the high frequencies and small differences for the low frequencies as expected. At the ports the currents are the same.
Fig. 2 - Radiated, Injected and Difference of Currents for 300 MHz, Coherent Injected Sources.

Fig. 3 - Radiated, Injected and Difference of Currents for 300 MHz, Magnitude Only Injected Sources.

Fig. 4 - Radiated, Injected and Difference of Currents for 100 MHz, Coherent Injected Sources.
Discussion of the Results and Recommendations

The first conclusion implies that if an EUT is linear and reciprocal then, in most cases, there is no need to perform injected tests. Because of linearity the actual values of the voltages and currents, anywhere in the EUT, for the full value of the fields required in the Radiated test, can be obtained by scaling up the results from low level radiated test measurements.

The second conclusion states that, if the EUT is nonreciprocal or if the EUT becomes non-linear for the incident field level required in the radiated test, then there is no way to guarantee that both tests are equivalent even at the ports. This violates the most basic assumptions that were necessary to establish the equivalence of both tests.

A good physical understanding of why nonlinear behavior cannot be tolerated is by observing the large differences in the currents excited throughout the EUT by both tests, Figs. 2, 4, 5. If a nonlinearity is present at a location where both currents differ by several dB, then the nonlinearity will be excited in quite different ways in each test producing different harmonics in number amplitude and phases.

A case could be made for the lower frequencies where the EUT is, say, less than 1/10th of the wavelength. Since the currents cannot differ by more than a few dB then perhaps the tests could be equivalent. This probably would be true for the most simple EUTs, like a piece of cable used in the simulation carried out here. Then no injection tests are needed as pointed out before. If amplifiers and/or logic devices are involved then the EUT is nonreciprocal and again, even at very low frequencies, the equivalence could not be established.

The non-reciprocal behavior can be easily understood by considering an amplifier. An injected source at the amplifier output could not excite the circuitry connected at the amplifier input. This is because, in most amplifiers, the input and output are completely disconnected. The radiated test has no such limitation, it illuminates the circuits connected to the input as well as to the output of the amplifier. Most logic chips are also non-reciprocal. Their presence prevents establishing the equivalence of both tests.

References

