

Using Finite Element Software to Predict EMC Performance from Electrically Small Sources

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ABSTRACT

A major limit of the finite element method in the past has been its relative difficulty to model three-dimensional open configurations found in EMC problems. MSC/EMAS with its open boundary elements now enables problems to be solved in three-dimensions that were previously considered solvable only with Method of Moment (MoM) codes and other techniques. MSC/EMAS is used here to accurately compute radiation fields from an electrically small source (less than a wavelength) that was previously solved with method of moments codes, and then to analyze printed circuit radiation that cannot easily be predicted by MoM.

INTRODUCTION:

Often, the most difficult to predict sources of EMI are from objects smaller than a wavelength.[1] When designing for EMC/EMI we tend to analyze the system with circuit and transmission line theory. This tells part of the story but not the full story. As Einstein once said "Everything should be made as simple as possible, but no simpler". Circuit and transmission line theory are simplifications of Maxwell's Equations. To help understand the limitations of circuit and transmission line theory EMC/EMI texts have introduced the concept of differential mode and common mode current. Common mode current for a cable is the component of the cable current that flows in the same direction on all conductors as opposed to differential current which flows in opposite directions using different conductors in the same cable. For traces on a printed circuit board the distinction is not as clear. Depending on your frame of reference, it can be very confusing as to what is differential mode and what is common mode current. A simple explanation is that differential mode current is what traditional circuit theory explains and that common mode is added to explain the difference between Maxwell's Equations and circuit theory. Much has been written about differential mode and common mode current and its effects on radiated emissions.[2,3,4] Differential mode emission can be controlled relatively easily by circuit layout.[3] In most practical configurations, the common mode current is found to dominate the radiated emissions. A class of techniques, known as full-wave methods, which use Maxwell's Equations can be used to determine the radiated emissions without assuming the currents are differential or common mode. These methods include the Method of Moments (MoM), Finite Element Method (FEM), and Finite Difference-Time Domain (FD-TD). In this paper we will concentrate on the first two. The advantage of FEM over a MoM is that complicated, real world geometries can easily be modeled. The problem in the past with FEM is that three-dimensional open boundaries could not be easily modeled. The new version of MSC/EMAS handles the open boundaries very well, with open boundary elements, as can be seen in the first part of the paper where the two methods are compared for a simple test problem.

DISCUSSION:

The test problem used for the comparison of the MoM to FEM is a small loop circuit consisting of a voltage source and a load resistance connected to a long wire as shown in Figure 1. The MoM results are from a

paper written by Todd Hubing and Frank Kaufman.[1] The MoM codes used were WIRES and NEC.[5,6]

For the first part of the problem the maximum radiated electric field at 3 meters was calculated for the loop only (without the long wire). The results are shown in Table 1. From the table we can see that both methods give the same result for the simple loop. The measured field strength was 25 dB(μ V/m), indicating good agreement between the models and measurement.

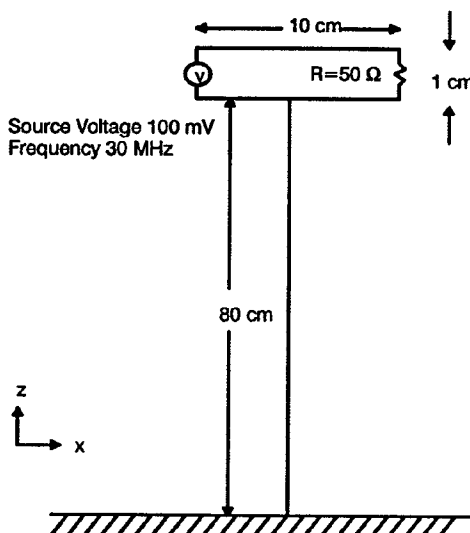


Figure 1 Small loop with attached wire to ground plane.

3-Meter Maximum Electric Field Strength dB(μ V/m)			
	MoM	FEM	% difference
loop only	24.0	24.0	0
loop with long wire	42.6	43.5	2.1

Table 1 Comparison of MoM verses FEM technique for circuit in Figure 1.

The current component distributions for the long wire configuration (Figure 2) are given in Table 2. The wires in the FEM model were given a larger cross-sectional area than in the MoM model which accounts for the higher currents in the FEM model. The important thing to notice from Table 2 is that the currents in the long wires are three orders of magnitude less than in the loop and yet it is these small currents that dominated the radiated emissions as shown in Table 1. The electric field from the loop current is 19 dB(μ V/m) less than that with the long wire even though the current on the long wire is three orders of magnitude less than the loop currents.

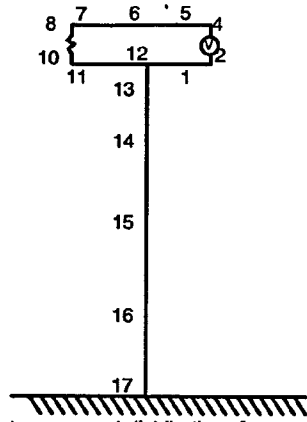


Figure 2 Current component distributions for the long-wire configuration.

position	Current (μA)			
	MoM		FEM	
	REAL	IMAG	REAL	IMAG
1	1635.7	-760.4	1813.9	-560.0
2	1635.5	-758.7	1813.8	-562.3
4	1635.4	-759.2	1813.7	-562.9
5	1635.0	-763.8	1813.5	-565.6
6	1633.7	-771.5	1811.0	-580.0
7	1631.7	-778.8	1808.8	-594.8
8	1630.3	-782.9	1808.2	-597.4
10	1630.3	-783.5	1808.1	-598.0
11	1631.0	-782.2	1808.4	-597.4
12	1632.0	-779.3	1811.0	-580.0
13	3.4	15.7	3.8	23.4
14	3.4	15.5	3.2	19.4
15	3.1	14.2	3.2	18.6
16	3.3	14.5	3.2	18.8
17	3.3	14.6	3.3	18.9

Table 2 Current component distribution for the long-wire configuration shown in Figure 2.

Figure 3 shows the mesh distribution of the FEM model. The mesh density is greatest near the wires. The open-boundary elements are applied to the surface of the hemisphere at a distance of $R = 4$ m. The bottom of the hemisphere is constrained to be a perfectly conducting ground plane.

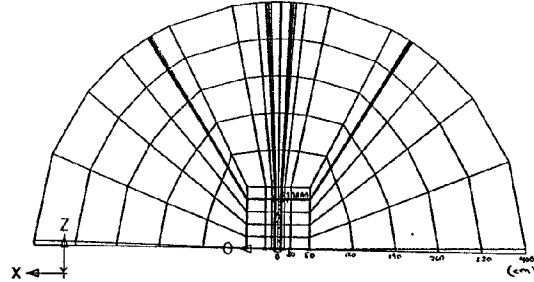


Figure 3 Cross-sectional slice of the xz-plane for $y=0$ of the FEM model.

Figure 4 dramatically shows the effect of the long wire on the radiated emissions of the circuit. The cutsurface shown is the xy plane with $z=80.5$ cm. This is the plane through the center of the loop parallel with the ground plane. From the top figure we see a loop pattern with the maximum electric field of 22 dB($\mu V/m$) at 3 meters. The bottom figure shows the dramatic effect of the long wire in that the field pattern is now that of a mono-pole with a maximum electric field of 43.5 dB($\mu V/m$). MSC/XL which is the pre and post processor for MSC/EMAS enables one to see clearly the field patterns of the two configurations.[7]

Circuit and Transmission line models are not able to predict the radiated emissions from the circuit in Figure 1. The power of the full-wave method is shown in its ability to model possible sources of EMI/EMC, such as found in Figure 1. FEM with the open boundary elements is now able to solve three-dimensional open boundary problems. The FEM technique has been shown to be a useful tool in modeling the radiated emissions of a simple circuit. FEM results agreed within 2.1 percent of the results obtained with MoM. FEM also has the advantage of being able to model complicated geometry that would be very difficult with a MoM technique. The next part of the paper will analyze printed circuit radiation that would be difficult to predict by MoM.

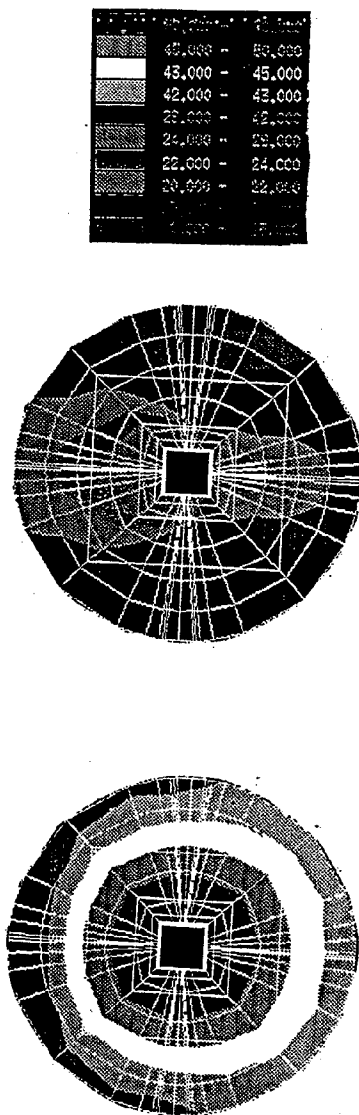


Figure 4 Top figure shows the electric field magnitude for the loop only. The bottom figure shows the electric field magnitude for the loop and long wire.

Part II

INTRODUCTION:

Automotive components usually have power and ground leads attached to a PCB. These circuits can radiate unwanted electromagnetic energy. MSC/EMAS was used to predict radiated emissions of a test component. A PCB consisting of an oscillator and two long traces of various widths is connected to a long

wire. The PCB and the long wire are 1 m above the floor in a shielded room. The electric field is determined at a distance of 1 m from the Device Under Test (DUT) for various trace widths. The common mode current is calculated for the long wire and compared with the electric field produced at 1 m. A relationship between trace width and common mode current on the wire is developed.

DISCUSSION:

MSC/EMAS was used to predict the radiated emissions from four different printed circuit board traces with a 2.235 meter long wire attached. The configuration of the model is shown in Figure 5 which simulates a shielded test room. A 100 mV voltage source at 30 MHz was the excitation for the model.

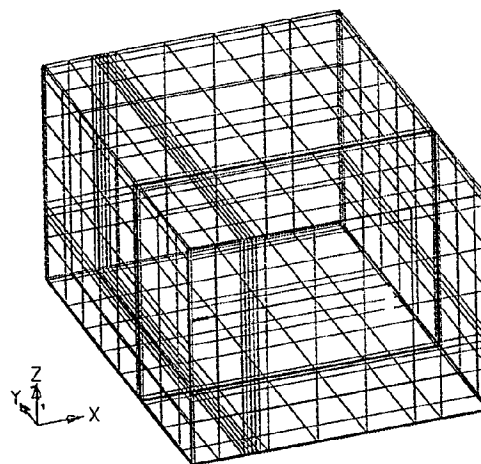


Figure 5. The FEM model of the test set up is shown. The shielded room is 3.66 x 4.88 x 3.05 meters. The PCB and attached 2.235 meter wire is 1 meter above the floor of the room.

The boards are 1.5 millimeters thick glass epoxy with a dielectric coefficient of 4.6. The wide and narrow traces are 2.54 centimeters and 0.5 millimeters wide and 15 centimeters long, respectively. The traces are separated by 2 millimeters and are terminated with a 330 ohm resistor.

The radiated fields from the four different PCBs are listed in Table 3. From the Table we can see that the electric field 1 meter from the center of the wire and 1 meter above the floor is a maximum of 56.1 dB(μ V/m) for the case (d) and minimum of 49.0 dB(μ V/m) for the case (c). It is interesting to note that just because there is asymmetry doesn't mean the fields will be worse. Case (c) has the lowest electric field and (d)

has the highest even though they are both asymmetrical.

1 m from center of harness, 1 m above floor 100 mV, 30 MHz source				
Electric Field dB(μ V/m)				
PCB Layout	X	Y	Z	Magnitude
a) Wide traces	-11.1	51.6	-15.5	55.0
b) Narrow traces	-18.2	45.5	-14.0	50.9
c) Asy (antenna on wide trace)	-11.6	45.3	-14.9	49.0
d) Asy (antenna on narrow trace)	40.4	-38.4	6.7	56.1

Table 3 Electric field predicted from MSC/EMAS at a location 1m from the center of the harness and 1m above the floor in a shielded room.

PCB Layout	Maximum Common Mode Current on Wire (μ A)
a) Wide traces	0.47
b) Narrow traces	0.38
c) Asy (antenna on wide trace)	0.27
d) Asy (antenna on narrow trace)	0.59

Table 4 Maximum common mode current on wire attached to PCB

Radiation occurs when an electric charge is accelerated, or in terms of current, when there is time changing current. Therefore at 30 MHz the two symmetrical traces on the PCB will radiate electromagnetic energy. We have shown in the first part of the paper that when a wire is attached to the circuit, the common mode current on the wire will dominate the radiated emissions. The question that needs to be answered is what effect geometry plays in producing common mode current.

Figure 6 shows the relationship between the attached wire and common mode current. From the figure we can see that if we increase the capacitance C_c the common mode current will also increase. Two ways to increase the capacitance are to bring the metal objects closer together or increase the surface area. One would expect that a wide trace opposite the attached wire would increase the capacitance C_c and thus increase the common mode current and this is exactly what we see in cases (d) and (a), as shown in Table 4. Case (a) has a larger capacitance C_d than case (d) and therefore I_c will be less, as shown. Cases (b) and (c)

both have a smaller C_c than (a) and (d) and therefore smaller I_c , as shown in Table 4. Case (c) has a larger C_d than (b) and thus will have a lower I_c , as shown in Table 4. In the next part of the paper we will look at the effect of adding another wire to the PCB.

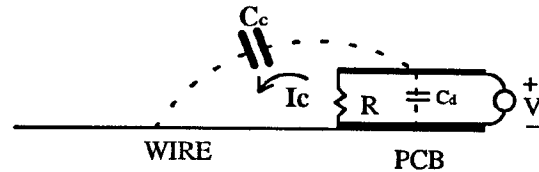


Figure 6 Common mode current due to the capacitance between the PCB trace and the attached wire. As C_c increases I_c also increases.

PART III

INTRODUCTION:

MSC/EMAS was used to analyze a finite element model of a radiated emissions test. A PCB consisting of a 40 MHz oscillator, with a 100 mV sinusoidal output is connected to two 15 cm long, 2.5 cm wide symmetrical traces. The traces are then connected to either a one or two wire harness 1 m long. The PCB and harness are 1 m above the floor. The electric field is determined at a distance of 1 m from the DUT for two configurations. The configurations are: perfectly conducting walls (shielded room), and ground plane only (no walls).

DISCUSSION:

The effect of one vs two wires attached to a PCB and also the effect of the test room on the radiated electric fields will be determined. The PCB with one wire will present a different impedance to the source than the PCB with two wires. The question is whether the two wires which have both differential and common mode currents will radiate more than the one wire which has only common mode current.

Tables 5,6 list the electric field results from MSC/EMAS for three elements that lie in the plane $y=1m$. The element 2229 lies in the same plane as the PCB ($z=1m$), as shown in Figure 7. Tables 5,6 show that the test room affects the fields. The shielded room is shown to give about the same magnitude as the ground plane only, but the direction is changed significantly. The electric field is higher for the PCB with two wires than for one wire.

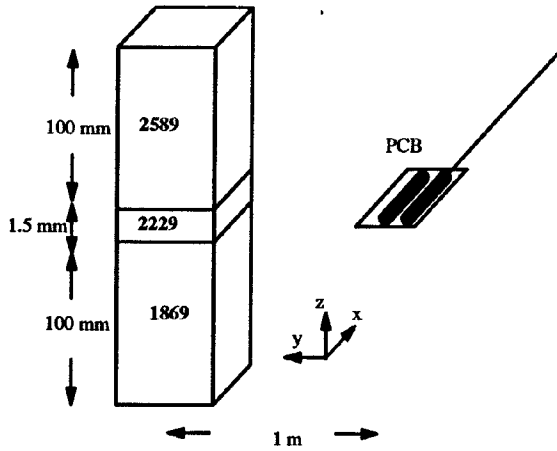


Figure 7 The location of the elements listed in Tables 5,6 relative to the PCB is shown in the figure.

Table 5(a) Electric Field (dBuV/m) for two wires in shielded room with perfectly conducting walls.

Element #	Ex	Ey	Ez	Magnitude
1869	10.81	-12.51	83.86	85.47
2229	17.99	-32.87	-77.95	86.49
2589	6.163	-2.867	-88.23	88.49

Table 5(b) Electric Field (dBuV/m) for one wire in shielded room with perfectly conducting walls.

Element #	Ex	Ey	Ez	Magnitude
1869	51.22	4.314	38.38	64.15
2229	62.63	-8.124	-5.628	63.41
2589	47.92	4.128	-43.34	64.74

Table 6(a) Electric Field (dBuV/m) for two wires above a ground plane (no shielded room).

Element #	Ex	Ey	Ez	Magnitude
1869	-49.35	-29.23	65.12	86.78
2229	-58.71	-54.30	-25.34	83.89
2589	-58.97	-32.03	-51.38	84.52

Table 6(b) Electric Field (dBuV/m) for one wire above a ground plane (no shielded room).

Element #	Ex	Ey	Ez	Magnitude
1869	-8.842	-18.65	60.85	64.25
2229	-3.682	-53.43	23.81	58.60
2589	-13.97	-30.74	-48.86	59.40

Next we will look at near and far field sources. We will start by looking at a infinitesimally small current element (Hertzian dipole) in free space. The simple Hertzian dipole consists of an infinitesimal current

element of length dl carrying a phasor current I that is assumed to be the same at all points along the element length. Figure 8 shows a figure of the Hertzian dipole.

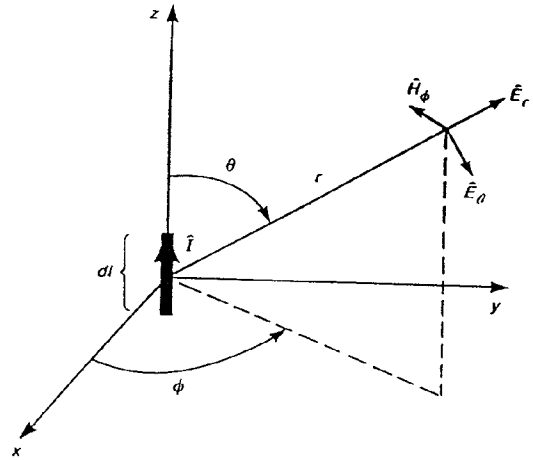


Figure 8 Diagram showing the Hertzian dipole.

The components of the electric field for the Hertzian dipole are

$$1(a) \quad E_r = 2 \frac{I dl}{4\pi} \eta_0 \beta_0^2 \cos \theta \left(\frac{1}{\beta_0^2 r^2} - j \frac{1}{\beta_0^3 r^3} \right) e^{-j\beta_0 r}$$

$$1(b) \quad E_\theta = \frac{I dl}{4\pi} \eta_0 \beta_0^2 \sin \theta \left(j \frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} - j \frac{1}{\beta_0^3 r^3} \right) e^{-j\beta_0 r}$$

$$1(c) \quad E_\phi = 0$$

where $\eta_0 = (\mu_0/\epsilon_0)^{1/2}$ and $\beta_0 = 2\pi/\lambda_0$.

The complete fields are very complicated near the antenna. The fields become much simpler to understand in the far field. For points near the antenna the $1/r^3$ and $1/r^2$ terms dominate. At farther distances the term $1/r$ dominates and this is referred to as the far field. For the Hertzian dipole this region between near and far field occurs at $r = \lambda_0/2\pi = 0.16\lambda_0$. As pointed out by Clayton Paul [8] the boundary between the near and far fields for other antennas is not simply $\lambda_0/2\pi$, as is frequently assumed. A more realistic choice is the larger of $3\lambda_0$ or $2D^2/\lambda_0$, where D is the largest dimension of the antenna.

When analyzing EMC/EMI it is important to determine if you are in the near or far field and if the source is magnetic or electric. MSC/EMAS enables you to determine this information at a test point by

looking at the wave impedance and phase shift between the electric and magnetic fields as follows.

To determine if the source is a magnetic field source or an electric field source we can plot $Z=E/H$. In the near field a high impedance field $Z>377$ ohms implies an electric field source and a low impedance field $Z<377$ ohms implies a magnetic field source. [3]

The following table is generated from an MSC/EMAS analysis which shows that we are in the near field of the transmitting antenna since Z is not equal to 377 ohms. The table also shows that the dominant coupling is electric field ($Z > 377$ ohms) for the single wire and that for two wires the coupling is a combination of electric and magnetic fields but still mainly electric ($Z > 377$ ohms).

FILE	element # 3024			element # 2229		
	E	H	Z	E	H	Z
one_h_ern	22.8E-5	57.0E-8	400	85.2E-5	75.7E-8	1125
two_h_ern	33.7E-4	15.0E-6	225	15.6E-3	19.3E-6	808
one_x	15.0E-5	17.1E-10	87720	15.0E-4	58.6E-9	25600
two_x	27.0E-5	25.6E-8	1055	21.0E-3	14.9E-6	1409

Table 7 The table lists the magnitude of the E and H field and the ratio $E/H = Z$ for two different elements. Element # 2229 is located one meter from the source and element # 3024 is located about three meters from the source.

The FILE one_h_ern is of a model with one long wire attached to a PCB one meter above a ground plane. The FILE two_h_ern is of a model with two long wires attached to a PCB one meter above a ground plane. For these two models we can see that Z is between 225 and 1125 ohms.

The FILE one_x is of a model with one long wire attached to a PCB one meter above the floor in a shielded room. The FILE two_x is of a model with two long wires attached to a PCB one meter above the floor in a shielded room. For these two models we can see that Z is much greater than 377 ohms.

The wave impedance is not really $Z = E/H$ but for a dipole orientated in the z direction the wave impedance is $Z_w = E_\theta/H_\phi$. In the far field they would give the same answer but in the near field the results would be different. We are not interested in the exact Z as much as what type of source we have, either electric or magnetic. From the above table we can see that the source is mainly electric.

Another method that can be used to determine if you are in the near or far field is to look at the phase shift between the magnetic and electric field. In the far field the electric and magnetic fields are in phase and represent power being radiated outward in the radial direction. In the region near the source the electric and magnetic fields are out of phase because it is a region of mainly energy storage. [9]

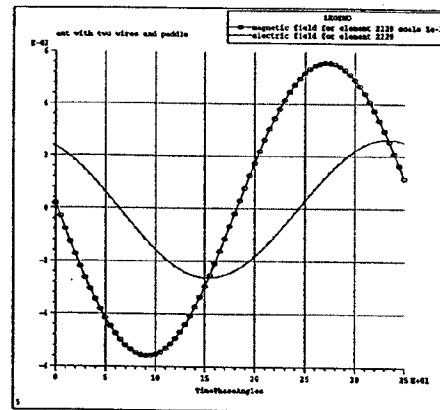


Figure 9 The graph shows the phase shift between the magnetic and electric field for the element 2229 located 1m away from the DUT.

Figure 9 is a plot of the electric and magnetic fields for element 2229. From Figure 9 we can see that the electric and magnetic fields are 65 degrees out of phase.

Figure 10 is a plot of the electric and magnetic fields for element 3024 for the case of an antenna above a ground plane (no shielded room). The electric and magnetic fields are less than 10 degrees out of phase. Element 3024 is further away from the source than element 2229 and as expected has less of a phase shift.

From the above discussion we have further proof that our test position (1 m from the DUT) is in the near field. MSC/EMAS can determine the electric field for a point in space. In the real world we use a measuring device that has a physical size and orientation which can influence the measured results. A receiving antenna in the near field complicates the problem even further. In order to compare MSC/EMAS

results with measured we would need to also model the receiving test antenna.

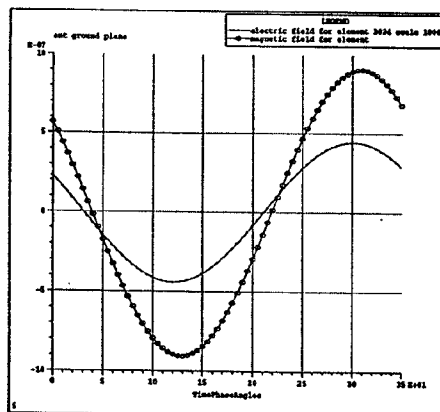


Figure 10 The graph shows the phase shift between the magnetic and electric field for the element 3024 located 3m away from the DUT.

It is expected that the PCB with two wires will have a lower impedance due to the capacitance between the wires, and thus have a higher differential current flowing on the PCB traces. Table 8 shows this to be the case. From Table 8 we can see that the PCB with one wire presents a resistance from 83 to 91 ohms, and that a PCB with two wires presents a resistance from 2.3 to 4 ohms. From the table we can see that the shielded room has an effect on the load the source sees, and will therefore influence the amount of current flowing on the PCB traces and attached wires.

Table 8 Table lists current and resistance a 100 mV source sees for different configurations.

configuration	current element # 33 (amps)	resistance (ohms)
one wire, ground plane only	11e-4	91
one wire, perfectly conducting walls	12e-4	83
two wires, ground plane only	25e-3	4
two wires, perfectly conducting walls	44e-3	2.3

The important thing this shows us is that the load the source sees is not constant. When modeling it is easy to produce an ideal source but in the lab it is much

more difficult and this is a common source of error between modeled and measured results that is commonly overlooked.

There will be a phase shift between the transmitting antenna (DUT) and the receiving test antenna. Part of the shift will be due to the distance between the transmitting and receiving antenna. In free space this would simply be the separation between the two but in a shielded room we also have the many reflecting surfaces that add their own phase shift. The reflecting surfaces will also add a 180 degree phase shift for electric field components tangential to the surface besides the shift due to path length.

From equations 1(a),(b) we can also see that in the near field the $1/r$, $1/r^2$, and $1/r^3$ terms are all out of phase with each other.

SUMMARY:

Circuit and Transmission line models are not able to predict the radiated emissions from simple circuits. The power of the full-wave method has been shown in its ability to model possible sources of EMI/EMC. FEM with the open boundary elements is now able to solve three-dimensional open boundary problems. The FEM technique has been shown to be a useful tool in modeling the radiated emissions of a simple circuit. FEM results agreed within 2.1 percent of the results obtained with MoM. FEM also has the advantage of being able to model complicated geometry that would be very difficult with a MoM technique.

Printed circuit radiation has been analyzed that would have been very difficult with a MoM code. The analysis has shown comparison between the radiated emissions of a PCB connected to a one or two wire harness is difficult to predict in general. The results depend on test conditions; shielded room, type of test antenna, if in near or far field, and nearness to metal objects. MSC/EMAS can be used to make the comparison if the model includes the right parameters.

CONCLUSIONS:

The FEM technique can be used to model EMC/EMI problems. Complicated models of printed circuit boards with attached wires have been modeled.

FEM has recently been used to model radiated emissions from a shielded box with a lossy seam gasket, and to calculate L and C matrices for complicated geometries.[10]

The location of the automotive electronic compass in the past had been a concern of packaging and not

performance. MSC/EMAS was used to perform a finite element analysis of a car's magnetic field distribution to determine the location of the electronic compass for optimal performance. The analysis also characterized the various electronic components' potential to interfere (EMI) with the electronic compass performance.[11]

FEM has also been used to analyze the effects EMC/EMI test chambers have on experimental results.[12]

The FEM technique is a powerful method to solve a wide range of EMC/EMI problems. FEM has always handled complicated geometries well and with the new open boundaries it can solve problems that were once the domain of MoM.

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