RF EM SUSCEPTIBILITY ANALYSIS OF HIGH-SPEED CIRCUITS USING MOM COMBINING WITH CIRCUIT-BASED METHOD

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Abstract: Full-wave numerical technique combining with the circuit-based method is used to investigate RF electromagnetic susceptibility of shielded high-speed circuits. The method of moment based on the electric field integral equation for the mixed geometries of wire and surface is developed to analyze the problem of shielding container with cables excited by EM waves or applied voltages. An equivalent source model to external RF EM interference is extracted and delivered to the circuit-based model of internal high-speed circuit for further EMS analysis with the circuit-based method. This approach balances efficiency and accuracy.

Key words: Electromagnetic susceptibility, the method of moment, radio frequency, equivalent source, SPICE model.

1. Introduction

The requirements in modern electronics lead to the importance of both electromagnetic interference (EMI) and susceptibility (EMS) [1]. Although historically emission problem has had priority over immunity for various reasons, the latter is becoming increasingly important with the presence of European EMC directive and other standards, and higher speed and density in electrical design [2]. It is essential that EMS should be considered in the early design phase to reduce design cost and time to market.

EMC modeling has become popular over the past few years because of the availability of software and the drive to reduce design cycle [3-4]. However, most focus has been on radiated emissions and little work has on EMS prediction. Due to complexity, it is necessary to use full-wave numerical techniques to evaluate the pickup of energy from external EM interference by high-speed system. However, they are intensive in computational time. On the other hand, traditional circuit-based method with lumped-circuit models is very efficient in computation and also valid and accurate if suitably handled.

In many applications, open cables are used to interconnect or power the shielded equipment, where external RF (radio frequency) interference energy induces currents onto cables and then is guided into internal sensitive high-speed circuits. The analysis to this here divides it into two sub-problems. The induced current is first calculated with the electric field integral equation formulation solved via the method of moment [5-6]. A MOM solver for the mixed geometries of wire and surface is developed to study external problem in RF EMS analysis of high-speed circuit. An equivalent source model to external EM interference is derived from numerical evaluations and delivered to a circuit-based model for susceptibility analysis of internal high-speed circuits with circuit-based solver like SPICE.

2. The MOM Method Using the Electric Field Integral Equation

In RF EMS analysis of shielded high-speed circuits, external problem is calculated with the MOM method, where the electric field integral equation is used. Let $S$ denote the surface of geometrically arbitrary PEC thin wires and/or bodies. Wire and/or surface currents $\vec{J}(\vec{r})$ are induced on $S$ due to applied electromagnetic interference. The boundary condition requires

$$ \vec{E}'(\vec{r}) \cdot \vec{n} = 0 \quad \text{on} \quad S$$

where $\vec{E}'(\vec{r})$ and $\vec{E}'$ represent the scattered electric field due to the induced currents $\vec{J}(\vec{r})$ and the applied interference electric field, respectively. In terms of the magnetic vector and electric scalar potentials, the applied electric field is related to the induced currents with the following equation

$$ \vec{E}' = j\omega \mu_0 \int_{\Omega} \frac{\vec{J}(\vec{r}) \cdot \vec{r}}{4\pi R} \, d\xi - j\omega\epsilon_0 \int_{\Omega} \sqrt{\frac{\vec{J}(\vec{r}) \cdot \vec{r} - \vec{n}}{4\pi R}} \, d\xi$$

where $k$ is wave number of the incident wave, and $R = |\vec{r} - \vec{r}'|$ and $\vec{r}$ and $\vec{r}'$ are the arbitrarily observation point and source point on the scatterers respectively. This integral equation includes line and surface integration if the geometries consist of both wires and volumetric bodies.

Straight wire segment and planar triangular patch are used to model thin PEC wires and the surfaces of PEC bodies respectively in the MOM method because they have the ability to conform to any wire/surface boundary. With mechanical software, the geometries are created, and then a segment/patch
model is generated and output to a file with standard format such as nastran.

In order to obtain a solution of induced current, it is expanded with a series of current basis functions with unknown coefficients. For thin wire geometries, an interior node, defined as that common to more than two straight segments, are first identified. At an interior node common to two segments shown in Fig. 1, a triangle wire current basis function is defined

$$
\tilde{f}_n(\tilde{r}) = \begin{cases} 
\frac{\tilde{P}_n/\ell_n}{\tilde{r} \in S'_n} & \\
\frac{\tilde{P}_n/\ell_n}{\tilde{r} \in S_n} & \\
0 & \text{otherwise}
\end{cases}
$$

(3)

For an interior node common to \( n \) (\( n \) is larger than two) segments, any one among \( n \) straight segments is first chosen and \( n-1 \) bases can be obtained with the chosen segment and the rest \( n-1 \) ones respectively.

When the surfaces of PEC bodies are modeled with planar triangular patches, an interior side, defined as one common to more than two triangular patches, is

$$
\tilde{f}_n(\tilde{r}) = \begin{cases} 
\frac{\tilde{I}_n\tilde{S}_n/2A_n}{\tilde{r} \in T'_n} & \\
\frac{\tilde{I}_n\tilde{S}_n/2A_n}{\tilde{r} \in T_n} & \\
0 & \text{otherwise}
\end{cases}
$$

(4)

which has unique properties [4]. Similar to interior node for wire geometries, at an interior side common to \( n \) (\( n \) is larger than two) triangular patches, any one patch is first chosen and \( n-1 \) bases can be gotten with this chosen patch and the rest \( n-1 \) patches respectively.

When a straight wire segment is attached to a surface, where an attaching point is a vertex of planar triangular patches modelling that surface, a junction base consists of that segment and all triangular patches common to that junction vertex and junction basis function is chosen as following

$$
\tilde{f}_n = \begin{cases} 
\frac{\tilde{I}_n}{2A_n} \tilde{P}_n & \tilde{r} \in T'_n \\tilde{P} \in S'_n \\
0 & \text{otherwise}
\end{cases}
$$

where \( A_n \) is the area of the \( n \)th triangular patch common to the junction vertex in the \( n \)th junction base and \( h_n \) is the height relative to that vertex, and

$$
\tilde{I}_n = \frac{\alpha_n}{\ell_n \sum_{j=1}^{N_i} I_j \tilde{f}_j(\tilde{r})}
$$

(5)

where \( \alpha_n \) is internal angle between two sides of triangular patch common to the junction vertex.

The current on the wires and/or the surfaces of PEC bodies is then approximated as

$$
\tilde{f}_n = \begin{cases} 
\frac{\tilde{I}_n \tilde{S}_n}{2A_n} & \tilde{r} \in T'_n \\
0 & \text{otherwise}
\end{cases}
$$

(6)

where \( N_i \) is total number of the base modeling the geometries and \( I_n \) is unknown coefficients. With the excitation of incident plane EM wave with arbitrary polarization and propagation direction \( \tilde{E} = E_0 e^{\beta z} \) or applied voltages, a linear system of equations are derived using the Galerkin’s method, and then the current on the wires and/or the surfaces are obtained through LU decomposition method.

3. Extraction of Equivalent Lumped Source
Model to External EM Interference

Using the electric field integral equation, the sub-problem due to external EM noise is solved via the method of moment. To couple this interference into internal high-speed circuit, an equivalent source circuit is extracted from the previous calculations. According to circuit theory, any circuit at two nodes can be equivalently considered as a parallel combination of short-circuit current with open-circuit impedance seen back to the actual source. For the shielding container with cables illuminated by external EM interference, the current \( I \) at the junction point where a cable is perfectly connected to the

$$
\tilde{f}_n = \begin{cases} 
0 & \tilde{r} \in T'_n \\
0 & \text{otherwise}
\end{cases}
$$

(Fig. 3 The equivalent source model to external EM interference.

container needs be calculated, then input impedance \( Z_{in} \) at that junction point needs be evaluated, both via the MOM method. The equivalent source model is
shown in Fig. 3, where $R$, $Z$, and $I$ are the input resistance, reactance, and current calculated before respectively. To use circuit-based method, $Z$ needs be converted into a lumped capacitance or inductance, dependent of its actual reactance. $Z_L$ accounts for leakage impedance to ground, depending on the way a cable is connected to the container. $Z_{cyl}$ if the cable enters into the container contactless. $Z_I$ is determined by the way the cable is connected to internal circuits. If it physically contacts a trace of the circuit, $Z_I = 0$. This method is still valid for the cases of multiple cables. After the equivalent source model is delivered to internal high-speed a circuits, circuit-based model is built, and then analysed with the circuit-based method, like SPICE solver.

3. Susceptibility Analysis of Three-Layer PCB Board to External RF EM Interference

A three-layer PCB board inside a PEC container attached with a signal cable is analysed, where the cable enters the container and is directly connected to a trace on the PCB board. The container has the size of $20cm \times 15cm \times 10cm$ and the cable has an arbitrary shape shown in Fig. 4. They are created with the software FEMAP and are meshed with triangular patches for the surface of the container and straight segments for the cable, also shown in Fig. 4. First,

![Fig. 4 Geometries of a shielding container and a cable and the elements after meshing.](image)

under the illumination of incident RF plane EM wave with the following electrical field

$$\vec{E} = \vec{E}_0 \cdot e^{j\omega t}$$  \hspace{1cm} (7)

the induced current on the surface of container and the cable is determined with the MOM method from 20MHz to 1GHz, where the cable is connected to the container. The current density on the surface of the container at 1GHz is shown in Fig. 5. The change of induced current at the point where the cable is connected to the container with frequency is shown in Fig. 6. The change of induced current in the cable at the point connecting to the box with frequency in Fig. 6, including amplitude and phase. Under the excitation of a gap voltage in the cable at the point connecting to the container, the induced currents are solved through MOM from 20MHz to 1GHz. The current density on the surface of the container under the excitation of a gap voltage at the connecting point at 1GHz.

![Fig. 7 Induced current on the surface of the container under the excitation of a gap voltage at the connecting point at 1GHz.](image)

![Fig. 8 The change of input impedance and equivalent capacitance at the connecting point with frequency.](image)

The change of input impedance and equivalent capacitance at the connecting point with frequency. into lumped capacitance because it is less than zero here, whose value is also shown in Fig. 8. It can be found that the change of capacitance with frequency
is very small and has a value around 0.2pF. Inside
the container, there is a three-layer PCB board with
the height each layer of $d = 0.2\text{mm}$, shown in Fig. 9.
15 traces are set in different layers which has the

cross section of $w \times h = 0.4\text{mm} \times 0.06\text{mm}$. The spacing
between traces is $s = 1\text{mm}$ and the length of straight
traces is $10\text{cm}$. External cable enters the container
unattached and is connected to the traces 13. To
model open-circuit situation at both ends of the
traces, which is the worst case from the viewpoint
of signal integrity, a large resistance $R = 10\text{ohms}$
is connected between all the ends and reference ground.
A SPICE model is built with the equivalent current
source model derived before as an excitation, then

analyzed with SPICE solver. The voltages across the
ends of traces and reference ground are extracted and
shown in Figs. 10 and 11, where the former is the
near-end voltage and the latter is the far-end voltage
with the change of frequency. It can be found around
750MHz, a large RF noise due to external EM
interference is examined, which might interfere the
normal operation of high-speed circuit in the system.

7. Conclusions

RF EM susceptibility analysis of high-speed circuit
inside shielding container with signal cables is
carried out in the paper, where the analysis is divided
into external and internal parts. For external problem,
full-wave numerical technique based on the electric
field integral equation via the method of moment is

used. A full-wave solver is developed for the mixed
geometries of PEC wire and solid bodies, which can
handle arbitrary geometries created by mechanical
and meshing software. An equivalent lumped source
model is developed from external problem analysis,
and then delivered to internal circuit-based model as
an equivalent excitation. The internal problem is
evaluated with traditional circuit-based method. This
approach balances the efficiency and accuracy, and a
practical application shows its validity.

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