An Efficient Hybrid Method for Calculating the EMC Coupling to a Device on a Printed Circuit Board inside a Cavity by a Wire Penetrating an Aperture

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ABSTRACT

An efficient hybrid method is developed for calculating the coupling to a device on a printed circuit board inside a cavity. The printed circuit board is connected to a wire or cable that penetrates through an aperture in the cavity enclosure. The method uses a combination of transmission-line analysis and a full-wave solver together with a decomposition of the problem into interior and exterior problems for maximum efficiency. Results are presented to verify the accuracy of the proposed method and to study the effects of cavity resonances on the coupling to a device inside the cavity.

Keywords: electromagnetic compatibility, EMC, electromagnetic interference, EMI, cavity, printed-circuit board.
Introduction

A printed circuit board (PCB) inside a conductive closure is a typical subcomponent of an electronic system. The coupling of an external incident electromagnetic wave to the PCB inside the enclosure is an important problem in electromagnetic compatibility (EMC), since the coupling of the incident wave into the enclosure can be very important in determining the signal levels at a device on the PCB.

Both PCB analyses and cavity analyses have received significant attention. For PCB analyses, many techniques have been used. For example, Ji et al. (1999) used the FEM/MoM method to analyze the radiation from a PCB. The partial element equivalent circuit approach (PEEC) which employs quasi-static calculations, has also been widely used to analyze PCB signals such as in the works of Archambeault and Ruehli (2001) and Ji et al. (2001). For cavity analyses, many studies have investigated coupling of electromagnetic waves to a simple element, such as a wire, inside the cavity enclosure. For example, Carpes et al. (2002) used FEM to analyze the coupling of an incident wave to a wire inside a cavity. Lecointe et al. (1992) analyzed a similar problem using the MoM.

The integration of both PCB and cavity analyses is necessary in order to analyze the coupling of an incident wave to a device on a PCB inside a cavity enclosure. The particular problem addressed here is the coupling from an aperture on the metallic enclosure, which may have a wire penetrating from the exterior. This penetrating feed wire may terminate inside the cavity without contacting the PCB, or it may make a direct contact with the conductive trace on the
PCB. The latter case typically results in the strongest EMC coupling mechanism, as is demonstrated here, and is the main subject of investigation.

One difficulty in the numerical analysis of such coupling problems is treating the disparate levels of feature size. The cavity dimensions may be on the order of a wavelength or more. However, on the circuit board the feature size is often much smaller than a wavelength. Furthermore, a complicated conductor trace pattern may exist on the PCB, requiring a fine level of discretization in a purely numerical scheme. Hence, a method that allows for an efficient analysis of the coupling to the component on the PCB without requiring a complete numerical discretization of the entire problem is desirable.

The purpose of this paper is to develop an approach that combines the PCB and cavity enclosure analysis together into a unified hybrid method that can be used to efficiently calculate the signal level at the input to a device on a PCB due to coupling from an incident exterior field in problems where a coupling wire penetrates an aperture. In particular, a Thévenin equivalent circuit is obtained at the input port to the device on the PCB. In the proposed hybrid method the PCB trace level is analyzed by using a separate analysis method, such as transmission-line theory, while the coupling of the incident field to the PCB is analyzed using a full-wave solver (Sharpe et al., 1998). The method decomposes the problem into separate interior and exterior problems, thus greatly increasing the efficiency of the computation. The decomposition is accurate provided the aperture is small and the PCB substrate is thin compared to the wavelength.
Both the Thévenin voltage and impedance can be found using a similar analysis. However, only the Thévenin open circuit voltage is discussed here because the impedance evaluation merely involves a similar short circuit calculation, and also because the input impedance of many digital devices on a PCB can be approximated as an open circuit, so that the Thévenin impedance is not required.

**Geometry of Coupling Problem**

Figure 1 shows a schematic diagram of the system under study. It consists of a coupling (feed) wire penetrating an aperture in a cavity. This wire connects to a transmission line that is part of a PCB trace. The PCB of thickness $h$ is assumed in the figure to reside at the bottom of the cavity and to extend horizontally across the dimensions of the cavity. Although not discussed here, the method can be extended to analyze configurations where the PCB is of finite extent and suspended within the cavity. A device (integrated circuit package, etc.) is mounted on the PCB, and connected to the PCB trace. An incident field illuminates the feed wire from the exterior. The goal is to calculate the Thévenin equivalent circuit that represents the connection of the complete system to the device. Although this requires the calculation of the Thévenin voltage and the Thévenin impedance, only the calculation of the Thévenin voltage is discussed here, which involves the calculation of the open-circuit voltage at the port to the device.

The signal at the open-circuit Thévenin port arises from several mechanisms. The first, and generally the largest contributor, is the direct current injection from the feed wire to the PCB trace. This results in a signal that directly propagates to the device port. The second mechanism is electromagnetic interaction between the current on the feed wire and PCB trace. This
interaction mechanism is of secondary importance when there is a direct connection between the feed wire and the PCB trace (as in Fig. 1), but is dominant when the feed wire makes no contact with the PCB trace. The third mechanism is the direct interaction between the aperture and the PCB trace. This mechanism is the weakest of the three, at least for small apertures. It is the only coupling mechanism present, however, when no feed wire penetrates the aperture. The analysis presented here focuses on the situation shown in Fig. 1, where a direct contact is assumed between the feed wire and the PCB trace. However, the case of no contact can also be easily treated as a special case.

Figure 1. A pictorial illustration of a feed wire that penetrates an aperture in a conducting cavity enclosure, and then makes contact with a conducting trace on a printed circuit board (PCB). The PCB trace leads to the input port of a device, such as an integrated circuit (IC). The arrows symbolically show that coupling to the device occurs through the direct current path as well as through electromagnetic coupling between the PCB trace and the feed wire and aperture.
Calculation of Thévenin Voltage

The hybrid method separates the calculation of the PCB analysis (using transmission-line theory) from the full wave analysis of the cavity enclosure and the feed wire, and furthermore, separates the problem into interior and exterior parts that are linked together via the voltage between the feed wire and the cavity at the aperture port. The steps in the analysis are outlined below.

Step 1

The problem is first separated into 2 parts: the cavity interior and the cavity exterior. Both parts are connected by the aperture. In the interior part, the aperture is shorted and replaced by a voltage source of 1V at the contact point between the feed wire and the interior cavity wall, as shown in Fig. 2.

The voltage source is initially set at 1 V for convenience (the value is arbitrary for the purposes of determining the input impedance seen by the source). In Fig. 2 the Thévenin port (originally connected to the device on the PCB) is shown open-circuited, and the voltage \( V^{th} \) to be calculated is labeled. The rest of the trace pattern on the PCB, which may be quite complicated, is assumed to terminate in one or more linear loads. For simplicity, Fig. 2 shows a single trace wire leading to a load \( Z_L \). Note that with the unit voltage source, the aperture input impedance, \( Z_{in}^{th} \), of the interior system is simply the reciprocal of the current to be determined at the voltage source. This will be obtained in Step 3 below.
Step 2

By assuming that transmission line theory can be used to model the PCB trace, a frequency-dependent lumped load, $Z_{in}$, can be used to replace the PCB trace at the junction between the feed wire and trace. Figure 3 shows the reduced model with the PCB trace replaced by the lumped load $Z_{in}$. (The substrate is also removed, although its effects are included in the transmission-line calculation used to determine $Z_{in}$). This approximation is accurate as long as the substrate thickness of the PCB, $h$, is small compared to a wavelength so that interactions between the feed wire and the trace are relatively small. For convenience, the current $I_w$ (which is a function of position) that exists on the feed wire when excited by the 1 V source is shown. The value of the feed-wire current at the contact point with the lumped load $Z_{in}$ (the junction between the feed wire and the original PCB trace) is labeled as $I_f$, and is of particular importance in determining the excitation of the PCB trace.
Step 3

A full-wave solver is used to analyze the interior problem of Fig. 3, in order to determine the current $I_w$ that exists on the feed wire. Of particular importance are the values of the current $I_s$ and $I_J$, at the source and junction points, respectively. The aperture impedance is then given directly by

$$Z_{in}^{ap} = \frac{1}{I_s}. \quad (1)$$

This aperture impedance is used in the calculation of the exterior problem, which is described next.

Step 4

In the exterior problem, the aperture is shorted by a perfect conductor, forming a closed cavity on the exterior. The feed wire is now connected to the shorted cavity wall at the original penetration point, with the aperture impedance $Z_{in}^{ap}$ at the connection point to the cavity wall. The aperture
impedance thus replaces the influence of the entire cavity interior, including the feed wire and PCB trace. The part of the feed wire external to the cavity remains the same as in the original problem. Figure 4 shows the resulting model for the exterior problem. The voltage across the load, $V_g$, is calculated by full wave analysis, assuming that a known incident field illuminates the structure in Fig. 4. The voltage, $V_g$, obtained from the full-wave analysis is then used as a voltage source in the interior problem to calculate the Thévenin voltage at the desired port. This calculation is done in Step 5 below.

![Diagram](image)

Figure 4. Geometry for the exterior calculation, in which the interior of the cavity is replaced by the aperture input impedance $Z_{in}^{AP}$.

**Step 5**

The known aperture voltage source $V_g$ is next used to excite the interior problem to find the current on the feed wire produced by the exterior incident field. That is, the interior problem of Fig. 3 is reconsidered, except that the actual voltage at the aperture $V_g$ is used instead of the 1 V
source. No additional numerical calculations are required to find the current on the feed wire from the source voltage $V_g$, since the current determined from the numerical solution of the problem of Step 3 is simply scaled by the factor $V_g$ to obtain the current due to the source $V_g$. The resulting feed wire current is then used to excite the PCB trace to find the voltage at the open-circuit Thévenin port on the PCB trace, as explained in the step below.

Step 6

The feed wire inside the cavity is removed and replaced by the current $I_w(\ell)$ that flows on it ($\ell$ is the arc length parameter along the wire). This current produces a voltage at the Thévenin port on the PCB trace via two separate mechanisms. First, the current that exists at the junction, $I_j$, excites the PCB trace by means of direct current injection at the contact point. Second, the current on the feed wire produces a field inside the cavity that electromagnetically couples to the PCB trace. The total Thévenin voltage can thus be written as

$$V_{th} = V_{th}^I + V_{th}^{EM},$$

where $V_{th}^I$ is the Thévenin voltage due to the current injection and $V_{th}^{EM}$ is the Thévenin voltage due to the EM coupling from the feed current. In order to separate these two mechanisms, it is helpful to introduce two ideal current sources at the junction as shown in Fig. 5. They inject $I_j$ and $-I_j$ into the junction, and therefore their combined effect is zero. This artificial addition is very useful, however, in physically separating the two mechanisms.
The upward-pointing source, which injects the current \( I_J \) into the junction, is responsible for \( V_{th} \). The downward-pointing source, which takes current \( I_J \) away from the junction, is lumped together with the current of the feed wire, \( I_W \). Taken together, these two currents form a continuous current that does not inject any net current into the junction. Therefore, this current can only contribute to the Thévenin voltage by means of electromagnetic coupling to the PCB trace. That is, this current is responsible for \( V_{EM} \). Each contribution to the Thévenin voltage at the port is discussed in more detail below.

**Injection Current**

The Thévenin voltage from the injection current, \( V_{th}^{i} \), can be found from transmission-line theory. Figure 6 shows the transmission line system used in the calculation. Because the calculation of the open-circuit port voltage from the current source in Fig. 6 is a standard transmission-line problem, no further details are warranted here.
Electromagnetic Coupling from the Feed Wire

Figure 7 shows the feed-wire current together with the downward-pointing ideal current source. Taken together they form a current system that electromagnetically couples to the PCB trace, but injects no current into the trace junction. The Thévenin voltage $V_{th}^{EM}$ due to this current is found from distributed transmission-line theory. In this calculation, the field within the cavity is found from the current on the feed wire and the current generator, *in the absence* of the PCB trace (but in the presence of the cavity and substrate). This *impressed* field $E^{imp}$ then produces a distributed voltage source along the transmission line of the PCB trace. The distributed voltage source is given by

$$V_d(\ell) = \hat{\ell} \cdot E^{imp}(\ell),$$

(3)

where $\ell$ measures distance along the PCB transmission line trace, and the unit vector $\hat{\ell}$ points in the same direction as the reference direction for the distributed voltage source $V_d$ (from $-$ to $+$).

If the PCB trace is really terminated with a vertical load as shown in Fig. 6, then a distributed source would also exist over the vertical length of wire that connects the load $Z_L$. 

Figure 6. Calculation of the Thévenin voltage from the injection current using transmission line theory.
Results presented later show that the effect of the distributed voltage source on the Thévenin voltage at the open-circuit port is usually small compared to the effect of the injection current, at least for cases where the substrate is fairly thin compared with a wavelength.

**Description of Test Geometry**

The sample problem selected for all of the results is shown in Fig. 8. A feed wire runs through a rectangular aperture on the side of a rectangular perfectly conducting cavity, and penetrates the cavity a distance of 20 cm before bending downward a distance of 14.9 cm to make contact with a transmission-line wire parallel to the bottom of the cavity. The radius of the feed wire is 0.25 mm, and it extends outside the cavity by a length of 12 cm. The feed wire is centered horizontally within the cavity along the dimension perpendicular to the transmission-line wire. For simplicity, there is no dielectric substrate, so the “substrate” is simply a spacing of height $h$ between the transmission-line wire and the bottom of the cavity. The transmission-line wire,
which models a length of PCB trace, is chosen as a round wire for modeling simplicity. The wire has a radius chosen to give a $100 \, \Omega$ characteristic impedance for this line. (The radius of the PCB line therefore changes as $h$ changes. For example, for a substrate height of $h = 1$ mm, the PCB wire has a radius of 0.3833 mm.) Unless otherwise noted in the results, $h$ is set to 1 mm. A 50 $\Omega$ load is connected at one end of the TX line. The transmission-line wire has length 26 cm, and the Thévenin port (the left end of the line) is located 10 cm from the closest perpendicular cavity wall. All other dimensions are given in Fig. 8.

Figure 8. Sample geometry used for all of the numerical results.

Under the assumption that the aperture is small, the hybrid method discussed above does not require knowledge of the aperture size. For numerical validation in which a complete EM
simulation of the structure is used, a square aperture of dimensions $6 \times 6$ cm is assumed, centered about the feed wire.

An incident plane wave is assumed propagating vertically downward (the negative $z$ direction), and polarized in the $x$ direction (the direction parallel to the transmission-line wire, pointing to the right). The incident plane wave has an amplitude of 1.0 V/m and zero-degrees phase at the origin (the bottom left corner of the cavity).

**Numerical Results**

The first numerical results presented compare different coupling mechanisms in order to provide motivation for the importance of the problem considered here (a feed wire penetrating an aperture and making contact with a PCB trace). Results are then presented to validate the hybrid method discussed above, and to illustrate the physics governing the voltage level that appears at the Thévenin port due to an exterior incident plane wave.

**Comparison of Coupling**

First, to introduce the importance of this type of EMC/EMI problem (i.e., a feed wire making contact with a PCB trace) results are shown for three cases, based on the geometry of Fig. 8. The three cases are shown in Fig. 9. Each part of the figure corresponds to a different coupling mechanism: (a) coupling through an aperture only, (b) coupling from a wire penetrating an aperture (without contact to the PCB trace), and (c) coupling from a wire penetrating an aperture and then making a connection to the PCB trace (the exact geometry of Fig. 8). In case (b), the feed wire continues through the aperture to the opposite side of the cavity where it makes contact.
and terminates. The first two cases are scattering problems solved using a numerical code that provides a full-wave solution (Sharpe et al., 1998). The last case is analyzed by the hybrid method (a numerical validation of the hybrid method for this structure is presented later).

Figure 9. Three different structures, which illustrate different coupling mechanisms. (a) Coupling through an aperture only. (b) Coupling from a wire penetrating an aperture but not making a contact with the transmission-line wire. (c) Coupling through a wire penetrating an aperture and then making a contact with the transmission-line wire.

Figure 10 shows the magnitude of the voltage at the Thévenin port for the first two cases, (a) and (b). Figure 11 shows that of case (c). The results show that the coupling from a wire penetrating an aperture with a connection to the PCB trace has the strongest effect on the PCB trace, in terms of producing the largest voltage at the Thévenin port. Case (b), with a feed wire present but not making contact with the PCB trace has the next highest level of coupling. Case (a), where the coupling is due entirely from the aperture, has the lowest level of coupling. In all cases, resonant
peaks are clearly visible. Because of the stronger coupling, the focus of this investigation is on case (c), and all subsequent results are presented for this case only.

Figure 10. Thévenin voltage due to coupling through the aperture only, and from a feed wire penetrating through the aperture (no contact with the transmission line).

The next set of results is concerned with a numerical validation of the hybrid method, as discussed previously. The various steps in the hybrid method are first validated separately, and then the final result is validated.
Validation Studies

In the hybrid method, the PCB transmission line is modeled as a frequency dependent lumped load by using transmission line theory (see Fig. 3). The accuracy of the transmission-line theory depends on several factors. One of the dominant factors is the height of the wire above the bottom of the box. The next result is introduced to study the effect of the height of the line. A line of 0.36 m length is located at the middle and at a height $h$ above the bottom of the box (the same box as in Fig. 8) as shown in Fig. 12. A current source feeds the line at 0.1 m from the open-circuit port. In addition, a 50 $\Omega$ load is connected at the other (right) end of the line. The wire radii is varied so that the characteristic impedance of the transmission line is always 100 $\Omega$.

Figure 13 shows a comparison of the voltage at the open-circuit port for different heights of the line above the bottom of the box. Also included is a result using transmission line theory (this result is independent of $h$). For the largest value of $h$ (3 cm), a result is also included for which
an infinite ground plane was assumed, with no box. The numerically-exact (full-wave) results were obtained by meshing the transmission line wire, and using a cavity Green’s function to account for the presence of the cavity in a moment-method solution (Sharpe et al., 1998).

Figure 12. The geometry used to test the validity of transmission-line theory for a line above the bottom of the cavity.

Figure 13. Magnitude of the voltage at the open-circuit port for different heights $h$ of the wire above the bottom of the box, for the structure of Fig. 12.
The results show that the voltage calculated by the full-wave solution with \( h = 1 \) mm agrees very well with that calculated by transmission-line theory. As the height gets larger, there is greater disagreement between the numerical full-wave result and the transmission-line theory result. The resonant effect of the box also becomes stronger as the height increases. At a 3 mm height, the numerical result completely disagrees with transmission-line theory. Comparing with the case for no box (infinite ground plane), the resonant effects of the box are seen clearly for this height. The result for the line above the infinite ground plane shows only a wire resonance while in the box the line shows both a wire resonance and cavity resonances. The unloaded box resonance frequencies are 0.48, 0.56, 0.61, and 0.75 GHz. The effects of the box resonances are more obvious as the height \( h \) increases. At a 3 mm height, the numerically-exact result shows very pronounced resonance peaks.

From these validation results, it can be concluded that the height of a PCB transmission line (i.e., the thickness of the substrate) should not exceed about 5 mm in order for the hybrid method to provide accurate results for the range of frequencies considered. The following results all assume a height of \( h = 1 \) mm.

The next validation step is to check the accuracy of the current on the feed wire for the interior problem of Fig. 2. The current at the source \( (I_s) \) and at the junction \( (I_j) \) in Fig. 2 are calculated by two methods. One, which is referred to as the ‘rigorous method’, is to model the feed wire and the transmission line numerically, using a moment-method code that incorporates a cavity Green’s function (Sharpe et al., 1998). The other method, referred to as the ‘transmission-line approximation’, uses transmission-line theory to replace the transmission line with a frequency-
dependent lumped load, and then numerically models the same feed wire connected to the lumped load. The lumped load is the input impedance at the junction with the feed wire, as calculated from transmission-line theory. Figures 14 and 15 show a comparison of the current magnitude at the voltage source and the junction with the transmission line, respectively, for a line height of 1 mm.

![Comparison of current magnitude](image)

**Figure 14.** Comparison of the current magnitude at the location of the voltage source for the interior problem shown in Figure 2.

The results show that the transmission-line approximation is quite accurate compared with the rigorous solution. Both solutions show the wire resonance (due mainly to the length of the feed wire) and cavity resonances within the range of frequency from 0.01 GHz to 0.8 GHz. (Two of the cavity resonances are identified and labeled for convenience, using the indexing notation $mnp$...
corresponding to the \(xyz\) directions, respectively.) However, a discrepancy is observed at some resonant frequencies, where the maximum current values are a bit different.

Next, the voltage contribution \(V_{th}^J\) at the open-circuit Thévenin port from the injection current \(I_J\) and the voltage contribution \(V_{EM}^{th}\) from electromagnetic coupling to the feed wire are shown in Fig. 16 for \(h = 1\) mm. It can be seen from the figure that the electromagnetic coupling from the feed wire has a stronger effect as the frequency increases. However, for most frequencies this coupling mechanism is small compared with the voltage induced by direct current injection at the junction.
The total voltage at the open-circuit Thévenin port in the hybrid method comes from summing the two contributions. Figure 17 shows a comparison of the resulting voltage from the hybrid method and that from the rigorous method for the height $h = 1$ mm. The rigorous method is
calculated by modeling the entire interior problem shown in Fig. 2 (the feed wire and the
transmission line) using a cavity Green’s function. The result shows that the hybrid method
provides good agreement in the frequency range of study. It also shows that the hybrid method
captures both wire resonances and cavity resonances.

The next validation step is to calculate the voltage $V_g$ at the aperture from the exterior problem
in Fig. 4. In this step, the aperture is replaced by a frequency-dependent lumped load, $Z_{in}^{AP}$. The
value of this load is calculated from Step 3 of the hybrid method. Figure 18 shows the voltage
$V_g$ obtained from Step 3 of the hybrid method, compared with that obtained by a numerically-
exact solution of the problem in which the entire structure is discretized.

![Figure 18](image_url)

Figure 18. Magnitude of the voltage at the aperture, $V_g$, calculated using the hybrid method and
also calculated using a numerically-exact solution of the entire problem (complete EM).
Both the rigorous solution and the hybrid method show good agreement, except at 0.57 GHz. This frequency corresponds to the (110) mode cavity resonance. The resonance at 0.15 GHz is an exterior box resonance. Resonances from the wire inside the box and from the cavity resonances are also clearly visible. Of course, the calculation using the hybrid method is much more efficient, since it only requires meshing the exterior problem, and not the complete problem.

The voltage at the open-circuit Thévenin port due to the incident plane wave (i.e., the desired solution to the original problem) is then calculated in the hybrid method by scaling the Thévenin voltage from the interior part (Fig. 17) by the aperture voltage $V_a$ obtained from the hybrid-method calculation of Fig. 18. Figure 19 shows the final voltage at the open-circuit Thévenin port due to coupling of the system to the plane-wave incident on the structure of Fig. 4. Also shown in the figure is the Thévenin voltage calculated by modeling the entire problem numerically using a moment-method code (Sharpe et al., 1998).

Figure 19 shows that the hybrid method gives good agreement with the rigorous numerical method, except at the second cavity resonant peak, corresponding to the (110) cavity mode. Both methods show an exterior box resonance, a wire resonance, and cavity resonances. The discrepancy at 0.57 GHz (the 110 mode) is caused by inaccuracy in the complete numerical solution, rather than in the hybrid method, at this frequency. For this mode, the cavity electric field is almost orthogonal to the aperture electric field (which somewhat resembles a coaxial-cable mode but with a square outer conductor). Therefore, this cavity mode has little radiation.
and hence a very high $Q$. The result from the “rigorous” numerical solution is not accurate at this frequency due to the extremely high condition number of the moment-method matrix, as shown in Fig. 20.

Figure 19. Magnitude of the voltage at the open-circuit Thévenin port for the structure of Fig. 4, illuminated by an incident plane wave.

The hybrid method is much more efficient than the rigorous numerical solution, since the numerical solution requires meshing of the entire structure, including the cavity, the feed wire, and the transmission line, which are on very different scales. To illustrate, the calculation in Fig. 19 took approximately 1.7 times as long with the rigorous numerical solution, compared with the hybrid method. (Because a cavity Green’s function was used for the interior calculation in the interior problem, the calculation time in the hybrid method is dominated by the calculation of the
exterior problem.) For structures involving complicated realistic PCB traces, this factor is expected to be even much larger.

Conclusions

An efficient hybrid method for analyzing the signal level at the input to a device on a printed-circuit board inside a cavity enclosure due to electromagnetic coupling to an external field has been formulated and tested. The method assumes that a feed wire penetrates an aperture in the conductive enclosure, and then makes contact with the printed-circuit trace that leads to the device on the board (the case where the feed wire does not make direct contact can be considered as a special case). The method allows for the complete Thévenin equivalent circuit for the structure leading to the device port to be obtained.

Figure 20. The condition number of the moment-method matrix versus frequency, for the “rigorous” numerical solution. The condition number is very large at the (110) cavity mode resonance.
Results demonstrate that this type of coupling can be very significant, especially at resonant frequencies of the structure. The hybrid method accurately captures the system resonances, including the resonances of the exterior enclosure, the resonances of the interior cavity, and any resonances associated with the feed wire inside the cavity. The hybrid method appears to give accurate results when the substrate thickness of the printed-circuit board is small compared with a wavelength.

The method has been numerically tested for a fairly simple structure, in which the printed-circuit board trace is assumed to be a simple length of straight transmission line, and the substrate permittivity is that of air. Nevertheless, the conclusions are expected to remain valid for more practical printed-circuit board geometries, as long as the substrate thickness remains small compared with a wavelength.

The hybrid method is much more efficient than a direct numerical modeling of the entire structure, and appears promising for the analysis of realistic and more complex printed-circuit structures inside metallic enclosures.

References


