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Influence of Resonances on the Huygens' Box Method

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***Abstract*—The Huygens' box (HB) method of replacing an arbitrary module inside an electronic apparatus with a set of current sources on a closed surface is discussed. A numerical study is performed, with a typical printed circuit board (PCB) representing the module placed inside a tight metallic enclosure. It is observed that the accuracy of the HB method is generally good except at a few resonant frequencies. Even previously proposed correction to the method that consists of including the main features of the module inside HB is not found to be very effective. The traces on the PCB and especially the parallel plate resonator formed by the ground plane of the PCB and the enclosure are identified as causing the resonances. We estimate that it is most likely the narrowband character of the resonances that considerably increases the sensitivity of the HB method toward small differences in the structure.**

I. Introduction

When development of an electronic apparatus comes to the prototype stage, and the subject fails the standard radiated emission test, it is very costly to make necessary changes. Therefore, there has been a significant thrust in the EMC community towards the "first time right" design of electronic devices. The ultimate goal is to obtain a methodology which would help the EMC specialist or engineer in predicting whether the developed apparatus will comply with the emission standard or not, while still in the design stage.

Electromagnetic simulation naturally serves as an essential tool in such methodology, but in order to accurately predict the radiated field, we need to know the detailed structure of the apparatus. This can be a problem in some situations, when some parts of the apparatus (modules) are provided by external vendors, for instance. A solution has been proposed in the form of a virtual construct, a Huygens' box (HB), which uses fields obtained from a near-field scan of the particular module as sources in the simulation [1].

The HB method has one challenge, however: one of the conditions under which the method is derived assumes homogeneous space around HB. This condition is, of course, hardly satisfied when the module, to be replaced by HB in simulation, resides inside the apparatus enclosure, with bunches of cables and other modules nearby. In our earlier work, we have demonstrated that violation of this condition may lead to significant errors in the near and far fields produced by the apparatus [2], [3], [4]. We have also tested a solution from [1] how to alleviate the problem—by including main features of the module inside HB, to act as a re-scatterer for the fields reflected from the nearby objects.

In this paper, we present a numerical study with a simplified printed circuit board (PCB), representing a typical module, placed inside a tight metallic enclosure. Following the HB method, the PCB is replaced by the corresponding HB and far-field errors resulting from this substitution are observed. We focus on the extreme values of errors and we find out that these occur at the resonance frequencies of the PCB and the enclosure. Moreover, the previously suggested alleviation by including main features inside HB seems not to be very effective at these frequencies, which requires detailed investigation.

We begin with the theoretical background of the HB method in Section II, where the underlying surface equivalence theorem and its consequences are explained. In Section III, the numerical experiment is described, and the many simulation scenarios are clarified. Section IV continues with presentation of the results and their discussion, and finally Section V concludes the paper.

II. Theoretical Background

According to the surface equivalence theorem, assuming linearity of the materials and the underlying environment, a structure generating electromagnetic fields can be replaced by a set of electric and magnetic surface current densities running on a surface entirely enclosing the structure [5]. These current densities $\vec{J}_s$, $\vec{M}_s$ are determined using the original electric ($\vec{E}$) and magnetic ($\vec{H}$) fields in free space:

$$\vec{J}_s = \hat{n} \times \vec{H}, \qquad \vec{M}_s = -\hat{n} \times \vec{E}, \tag{1}$$

where $\hat{n}$ is the normal vector oriented outwards the surface. Since the shape of the closed surface is typically a cuboid, the resulting virtual construct replacing the original structure is called Huygens' box. The fields inside HB are equal to zero, therefore we can remove any materials and consider the inner space as empty, greatly simplifying any subsequent calculations.

In practice, the E- and H-fields are obtained from a near-field scan of the module with unknown inner structure, which we want to use in the simulations. From (1) it follows that only components of $\vec{E}$ and $\vec{H}$ that are tangential to the surface are necessary. The equivalence theorem also assumes homogeneous space everywhere outside the surface. To satisfy this condition, the near-field scan should therefore be carried out without any obstacles around the module.

Nevertheless, when we use HB as a source in simulation, it is placed near other objects of the simulated apparatus (cables, enclosure) and not in homogeneous space. Violation of this condition leads to significant errors in the calculated near and far fields, as has been demonstrated in [3], [6]. The fields generated by HB are reflected back towards HB by any nearby obstacles and penetrate the HB (as the $\vec{J}_s$ and $\vec{M}_s$ currents are added and not impressed), creating non-zero fields inside HB. These fields are not met with the original structure, from which they could re-scatter back, as would be the case with the real module in the enclosure, and this naturally causes errors.

A remedy for this problem has been suggested in [7], [1]: to include important features of the module inside HB, so that the re-scattering can take place and eliminate the errors. This could be done even without detailed knowledge of the module, usually the dimensions of the substrate and the ground plane of the PCB are enough and including these leads to significant drop of the errors at most of the frequencies. At some frequencies, however, the errors were still high due to resonances between the module and the nearby object—a tight metallic enclosure turned out to be the worst case scenario.

In the following, a numerical experiment is described, where a typical PCB is placed inside a tight enclosure, and errors of the HB method are evaluated. The aim is to assess the influence of the resonances on the errors of the approach.

III. Numerical Experiment

The module is represented by a simplified test PCB with dimensions 225 × 150 mm, with three traces of 3 mm width on the top layer and a full metallic ground plane (Fig. 1). The substrate is made of 2 mm thick FR4 material, with dielectric constant 4.35 and conductivity 10^{-3} S/m. The first trace is excited with 50 Ω source and load impedances, the other two are floating. The PCB is placed inside a box-like metallic enclosure, with dimensions 450 × 300 × 40 mm, opened at the narrow end.

We have used our in-house finite-difference time-domain (FDTD) code to perform the simulations [8]. All metals in the simulations are represented by perfect electric conductors (PEC), i.e. losses are neglected. The perfectly matched layers (PML) serve as an outer boundary of the computational domain, imitating free space. The native resolution of FDTD method is 1 mm, and this is also the resolution of the HB.

Our frequency range of interest is up to 1 GHz, hence the near and far fields are evaluated at frequencies from 20 MHz to 1 GHz, with 20 MHz step. In addition, 9 frequencies are added at which resonances occur.

In total 6 simulation scenarios are recognized, as depicted in Fig. 2. In the first scenario (Fig. 2a), the PCB is simulated in free space and the E and H fields are recorded, just as with the near-field scan. The recorded fields are then used to calculate the current densities (1) to be used with the HB (denoted by red color). The second scenario (Fig. 2b) presents this HB radiating in free space, and the fields outside will,

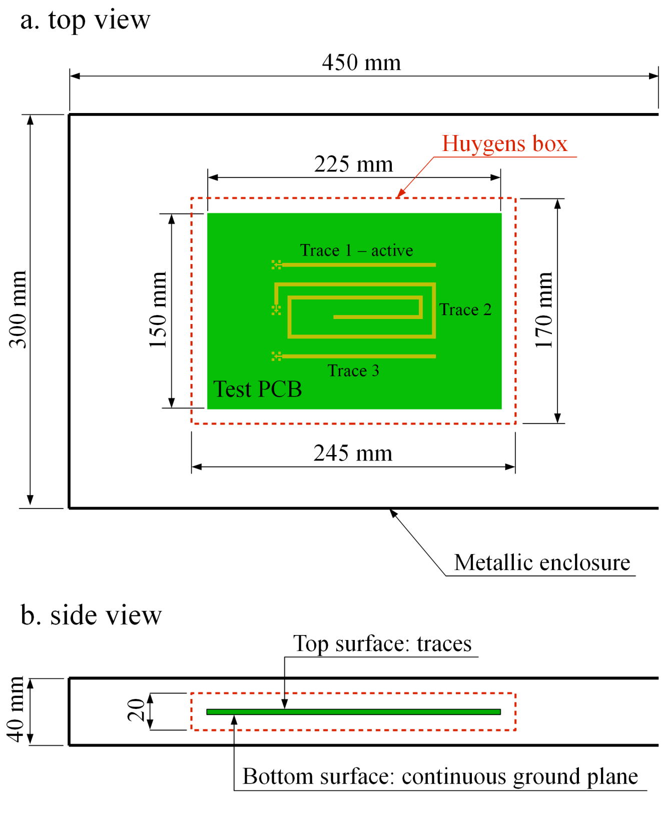

Fig. 1. Dimensions of the test PCB and the enclosure.

according to the equivalence theorem, be identical to Fig. 2a. We can use this empty HB as a source in an enclosure (Fig. 2d), but when comparing to the realistic scenario of the test PCB in the enclosure (Fig. 2c), there will be errors as we stated beforehand. Partial remedy can be to include the ground plane or the ground plane with the substrate as main features inside HB (Fig. 2e). Finally, the last scenario, where we include the full model without the sources, is supposed to bring the errors again to zero (Fig. 2f).

IV. Results and Discussion

In Fig. 3, the reflection coefficient of the first trace is shown, when the PCB is placed in free space and inside the enclosure. With the help of 3D visualization of the near fields (not shown), we identified the resonance frequencies of the PCB itself as originating from the second trace which has approximate length of 0.5 m (Table I).

When the PCB is placed inside the enclosure, additional resonances appear due to interactions between the ground plane of the PCB and the enclosure. These frequencies correspond to the 10, 01 and 11 resonating modes of the parallel plate resonator formed by the ground plane and the top side of the enclosure (Table II). We suppose that the resonator is excited by the loop formed by the active trace on top of the PCB and the ground plane, which is also the reason why the parallel plate resonator between the ground plane and the bottom of the enclosure is not excited.

The maximum far fields ($E_{\max}$) produced by the PCB in

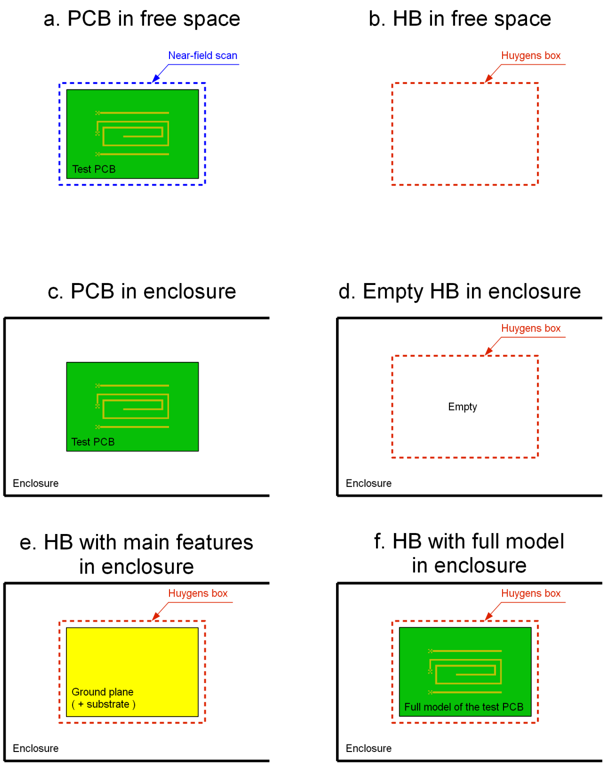

Fig. 2. Simulation scenarios.

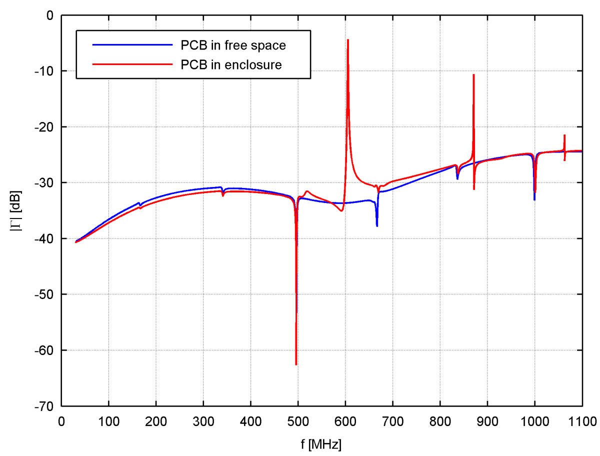

Fig. 3. Resonances of the PCB in free space (blue) and in the enclosure (red).

TABLE I. RESONANCE FREQUENCIES DUE TO THE SECOND TRACE ON THE TEST PCB

Mode	1	2	3	4	5	6
Frequency [MHz]	166.8	341.0	495.9	669.3	837.3	1000

TABLE II. RESONANCE FREQUENCIES DUE TO INTERACTION OF THE PCB AND THE ENCLOSURE

Mode	10	01	11
Frequency [MHz]	604.8	870.4	1062

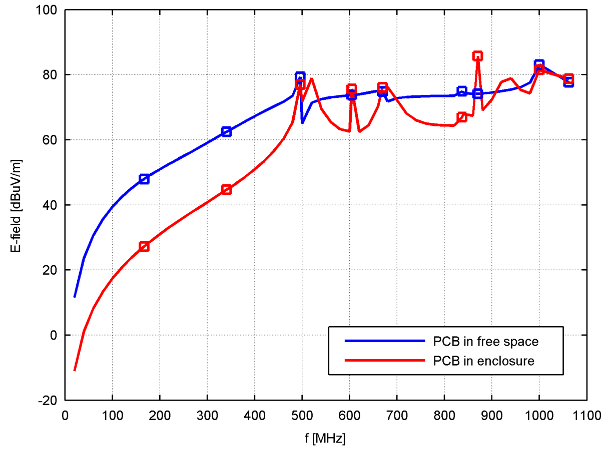

Fig. 4. Peak E-field at 3m distance radiated from the PCB in free space (blue) and in the enclosure (red). Resonances are denoted by squares.

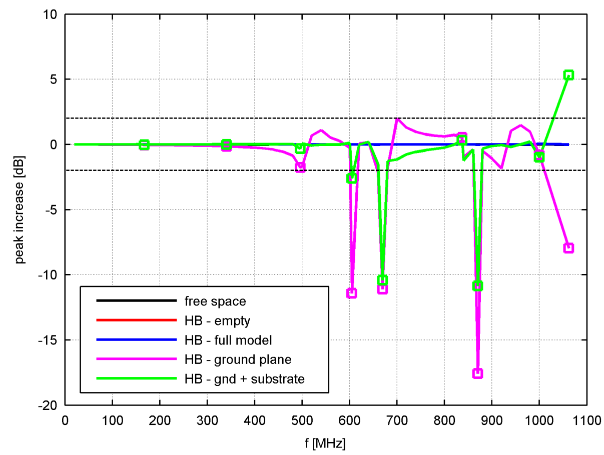

Fig. 5. Increase of the peak E-field due to HB method in free space (black) and in the enclosure: HB empty (red), HB with full model (blue), HB with ground plane (magenta), HB with ground plane and substrate (green). Resonances are denoted by squares.

free space and in the enclosure are plotted in Fig. 4. The E-fields are expressed in dB at 3m distance, always taking the higher value of the two polarizations—a procedure similar to the semi-anechoic chamber measurement standardized in CISPR 22, although we scan over the full hemisphere and do not take the influence of the floor into account. The far fields are generally higher when the PCB is not shielded by the enclosure, although this is not always the case, particularly at and near the resonances, denoted by squares.

The most important plot is, however, shown in Fig. 5 where we look at the errors introduced by the HB method. The error metric used is the peak increase, which is defined as the increase in the peak E-field value, as defined in previous paragraph, due to the HB method:

$$\text{peak increase} = E_{\max}(\text{HB}) - E_{\max}(\text{original}) \quad [\text{dB}] \qquad (2)$$

Five different errors are plotted in Fig. 5: the error for HB in free space (black curve, scenarios a versus b in Fig. 2), for empty HB in enclosure (red, c vs d), for HB with full model inside (blue, c vs f), for HB with ground plane inside (magenta) and with ground plane and substrate (green, both c vs e). The squares again highlight the data points at the resonance frequencies listed in Tables I and II.

The black curve is almost zero, since the surface equivalence theorem guarantees that the fields outside of HB will be recreated correctly in free space. The red and magenta curves (coinciding) show a significant error, when the HB placed in the enclosure is empty or when it includes only the ground plane of the PCB.

The fact that the error is the same in both cases might look like a mistake, but it is not—an inspection of the fields in the enclosure revealed that adding the ground plane into the calculation affects only the fields inside, but not those at the open end of the enclosure. As the open end acts as an antenna aperture, the radiated fields will be the same.

The error is only partially lowered by adding the substrate, and disappears completely when the full model of the PCB is added inside HB. The latter approach is, however, out of the scope of our premises, since we generally assume limited knowledge of the substituted module.

The outcome of the numerical study is that the errors can be kept within the $+/-2$ dB margin (denoted by dashed lines in Fig. 5) with basically all the strategies of filling the HB. The only exception are the resonances, where the HB method fails by underestimating the radiation by more than 10 dB. It is worth reminding that while underestimation of the far fields by the HB method may result in the final product failing the compliance test, the opposite situation when the fields are overestimated may be equally harmful—it means that the final product might become over-engineered in terms of EMC.

It can be seen that the errors at the parallel plate resonances do not drop to any acceptable levels even with the ground plane and the substrate of the original PCB added inside HB. This fact is quite surprising, taking into account that the only features making the difference from the full model are the traces and the 50 Ω loads. However, the observed resonances had very high Q-factor and correspondingly narrow bandwidth, and so it is well possible that even small differences in the material between the parallel plates might have caused detuning and large discrepancies when the frequency was fixed. That said, it might be of interest to look at the fields within slightly larger bandwidth, where the differences would probably cancel out—a subject for future work.

Regarding the process of near-field scan, one possibility how to reduce the necessary time and complexity is to make the lower surface of HB coincide with the ground plane of the PCB. The tangential electric field on the ground plane is zero, hence the magnetic current according to (1) vanishes. If we then also include the ground plane in the simulation, as in Fig. 2e, the electric current will effectively be short-circuited [5]. As a result, we do not need to measure either E- or H-fields in the area covered by the ground plane, and the fields outside HB in free space will still be correctly reproduced.

V. Conclusion

A numerical study of the HB method with typical PCB and a tight enclosure has been presented. It has been found that the resonances caused by the traces on the PCB and especially those between the PCB and the enclosure have strong influence on the predicted radiated fields, causing significant errors. None of the previously proposed remedies, such as including the ground plane and the substrate inside the HB, have been effective at the few frequencies where the PCB interacts with the metallic enclosure. High Q and the correspondingly narrow bandwidth of the parallel plate resonator has been proposed as the explanation for the sensitivity of the method.

We are currently investigating the HB method in various additional constellations, with other types of enclosures and PCBs, in order to generalize the results.

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