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How to Handle a Huygens' Box Inside an Enclosure

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***Abstract*— It has been suggested that it is possible to replace printed circuit boards with a Huygens' box (HB) representation obtained from a near-field scan in simulation of far-fields from an apparatus. However, the surface equivalence theorem requires that the environment outside HB is the same in the near-field scan and in the apparatus. This is seldom the case in common type of apparatus. This paper discusses how to handle HB inside typical enclosures. It is demonstrated that if the most important features of the printed circuit board are included inside HB, the introduced error in radiated fields caused by violating the surface equivalence theorem can be lower than 2 dB. It is also demonstrated that if the printed circuit board is galvanically connected to the enclosure, the near-field scan must be performed under same conditions.**

I. Introduction

Near-field scan has been used as hot-spot finding tool within the EMC society for many years. In recent years the interest in near-field scanning as a radiated emission pre-compliance test has considerably grown and the first proof of concept based on mainly simulations but also measurements has been carried out [1]-[3].

The very ambitious goal is that one should be able to do near-field scan of a printed circuit board (PCB) used in an apparatus and then use the measured near-field as a source for simulation of the far-field from the apparatus with chassis, cables etc.

There are two different dominating approaches to the far-field prediction. One approach uses the near-field as a basis for source reconstruction by help of an equivalent set of electric and/or magnetic dipoles [4] while another approach uses tangential near fields on a surface entirely enclosing the module [3]. These fields distributed on the closed surface, the Huygens' box (HB), then act as sources generating the same fields as the original module outside of this surface.

Both methods have problems when other structures are close to the source and interact with the source. The limitation of the latter method follows directly from the theory, namely that a correct prediction of the field outside the box requires that the near-field is measured in the exact same environments as in the final apparatus. [5] E.g. if the near-field is measured on a HB surrounding a PCB in free space, this HB cannot be used as source for simulation inside an enclosure not present at the time of measurement. The result may be inaccurate.

In a real apparatus, PCBs will of course be close to other structures. Studies on how to overcome difficulties like that are scarce. In [6] and [7], brief investigations on how to handle attached cables were done, nearby cable was studied in [8], and finally a ground plane was studied in [9].

PCBs are often placed inside metal enclosures like racks and these enclosures can both attenuate the radiated emission and increase the maximum radiated emission because of resonances. In [10], a PCB was placed in a small box with just one opening and the differences in the near-fields between the full model and HB model were observed.

In this paper, we would like to further elaborate on how large the far-field error will be with respect to the full model, and whether it is possible to reduce the far-field error by including some of the features from the radiating structure. In addition, we will also look at the differences when the PCB is galvanically connected to the enclosure compared to the situation with the PCB floating.

So the purpose of this paper is not to investigate the shielding effectiveness of different enclosures. The purpose is to investigate the error in the predicted far-field when a Huygens' box from a "free space" near-field scan is used inside an enclosure, that was not present when the near-field scan was carried out and how to reduce these far-field prediction errors.

In Section II the Huygens' box method is introduced. The objective with the simulations and a description of the models are given in Section III. The results are presented and discussed in Section IV and finally Section V draws the conclusions.

II. Huygens' box Method

In Fig. 1 a radiating structure is placed inside a boundary, S, marked with dotted lines. The surface equivalence theorem states that an arbitrary structure containing sources of electric and magnetic fields can be represented by electric and magnetic currents on a surface that encloses the structure, such that they produce the same field outside the surface while producing null field inside [5], [11]. The space around the HB must be the same in the original problem and in the equivalent problem. If the volume has a shape of a box, it is often called a Huygens' box.

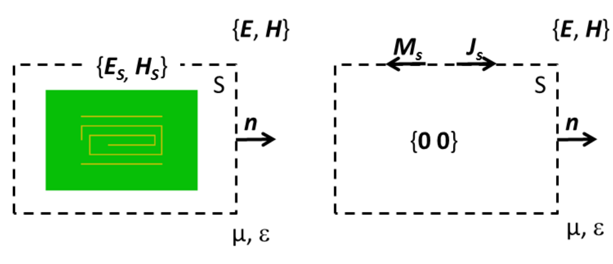

Fig. 1. The surface equivalence theorem.

The equivalent electric and magnetic currents are given by $\boldsymbol{J}_s = \boldsymbol{n} \times \boldsymbol{H}_S$ and $\boldsymbol{M}_s = -\boldsymbol{n} \times \boldsymbol{E}_S$, i.e. the tangential electric and magnetic fields on the surface of the closed box. In practice these tangential fields can be measured with near-field scans.

Many simulation tools can import HB and use the equivalent sources at the box surface as a source for simulations. We will call this "the Huygens' box method".

A. *The Limitation of the Huygens' Box Method*

The theory does not predict what happens if HB is placed inside a metallic enclosure or close to other structures and hence clearly violates the condition about having the same environment as the original and equivalent problem.

In the previous related work [6]-[10] it has been suggested to include the most important features of the structures such as ground plane and substrate. This is possible because the equivalent sources acting alone produce a null field inside the box. The idea is that the field reflected from nearby structures will be rescattered inside the Huygens' Box and hence acting like the original scenario.

B. *Including full model inside the Huygens box restores the fields outside in the presence of obstacles*

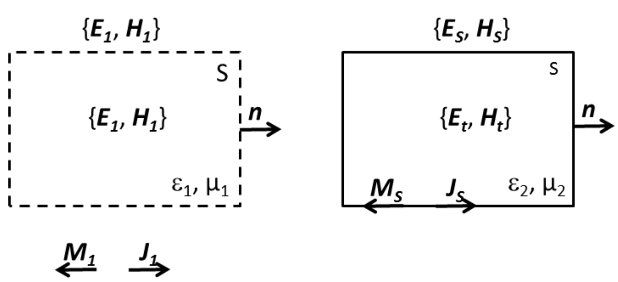

Fig. 2. The induction theorem.

Including the full model inside HB restores the original fields. It follows directly from an "inside-out" version of the induction theorem [5]. But let us start with the standard description of the induction theorem and assume a medium with constitutive parameters ε_1, μ_1, containing sources, and an obstacle with parameters ε_2, μ_2, see Fig. 2. The induction theorem states that the fields outside of the obstacle are given by a superposition of the original fields $\boldsymbol{E}_1$, $\boldsymbol{H}_1$ produced by the sources without the obstacle, and *scattered* fields $\boldsymbol{E}_S$, $\boldsymbol{H}_S$ which are generated by induced currents on the boundary of the obstacle, $\boldsymbol{J}_s = -\boldsymbol{n} \times \boldsymbol{H}_1$ and $\boldsymbol{M}_s = \boldsymbol{n} \times \boldsymbol{E}_1$,, and which radiate in the same environment, i.e. including the obstacle ($\boldsymbol{n}$ is the normal vector pointing outwards the obstacle). The fields inside the obstacle $\boldsymbol{E}_t$, $\boldsymbol{H}_t$ are the same, with the induced currents as well as with the total fields, which is a consequence of the boundary conditions as described in [5].

Our problem is arranged "inside-out", i.e. the whole region outside HB needs to be seen as the obstacle whereas the region inside corresponds to the background medium ε_1, μ_1. By reversing the direction of the normal vector $\boldsymbol{n}$ we arrive at the original formulas for currents on HB, which now produce the same fields outside (as in the obstacle above), and the scattered fields inside. Both regions must be present with their respective parameters, the region outside (the obstacle, ε_2, μ_2) and the region inside (ε_1, μ_1) with the full model of the PCB.

III. Test Setup

A. *The objective of the experiment*

The objective of this study is to investigate the HB method when the conditions for the surface equivalence theorem are not satisfied. By using only simulations we exclude the uncertainty of the measurements.

The workflow of the simulations is described in Figs. 1 and 3. A full model of the PCB was simulated in free space and the tangential components of the E- and H-fields on HB 10 mm around the structure was extracted (Fig. 1).

Next step was to place the PCB inside an enclosure and simulate the far-field (Fig. 3.a), which served as a reference. In order to quantify the error of the methods proposed in section II A, different simulation scenarios were carried out.

- The PCB was replaced by HB inside the enclosure (Fig. 3.b).
- The ground plane and the ground plane + substrate was placed inside HB (Fig 3.c)
- The full PCB model was placed inside HB (Fig 3.d).

After that we moved on to a setup where the PCB was connected to the enclosure in order to see, whether the connection to the enclosure requires changes in the method.

Again the HB was extracted from free space (Fig. 1), but in addition HB was extracted where the PCB was connected to an infinite ground plane (Fig. 4). In this scenario the HB enclosed the connections to the ground and the bottom side of the HB was 0 (no tangential field component in the infinite ground plane made of perfect conducting material).

The two different types of HB were then used in scenario b and c in Fig. 3.

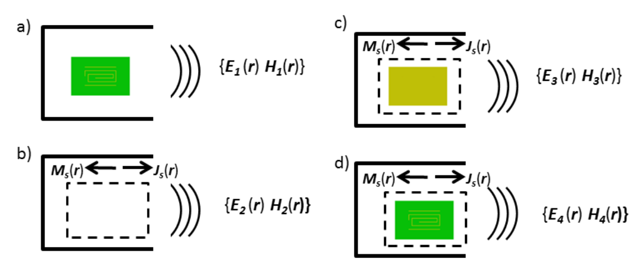

Fig. 3. Simulation scenarios.

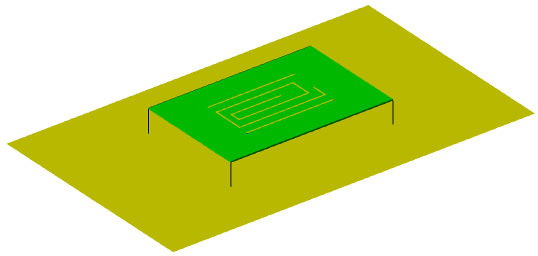

Fig. 4. A Huygens' box was extracted from a simulation with a PCB connected to an infinite ground plane.

In all scenarios the difference in the far-field between the Huygens' Box simulations and the reference was evaluated after the following metric:

$$\text{Peak increase} = 20 \cdot \log 10\,(\max(E_{\text{Huygens'}})/\max(E_{\text{reference}}))$$

where $\max(E_{\text{Huygens'}})$ is the maximum in the far E-field of the Huygens' Box model and $\max(E_{\text{reference}})$ is the maximum of the far E-field of the reference case. The maximum is taken across both theta and phi components - equivalent to the difference in two far-field measurements according to CISPR 22.

B. *The models*

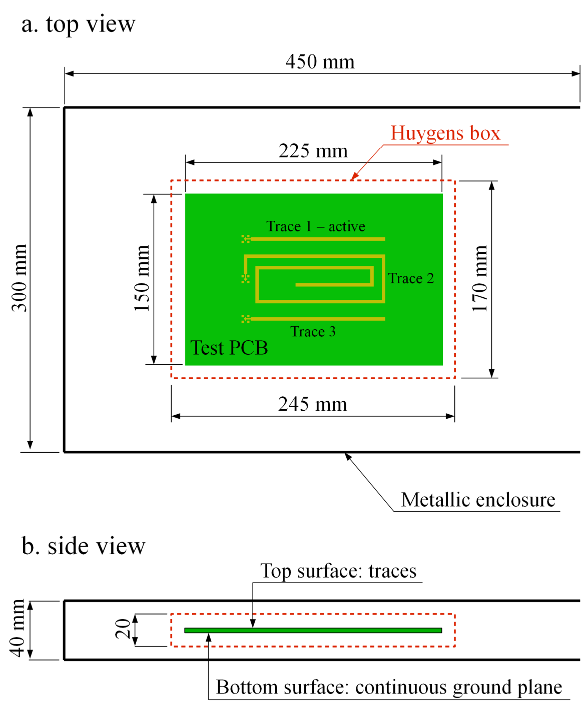

Fig. 5. The test PCB and enclosure 1.

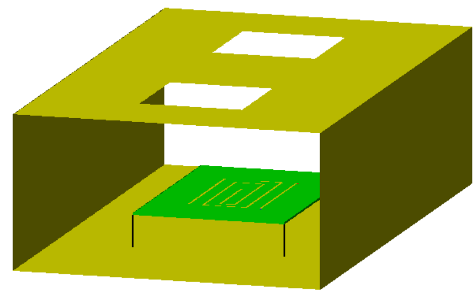

Fig. 6. Enclosure 2.

The simulated PCB is shown in Fig. 5a. A simple 150 x 225 mm PCB with three traces on the top layer and full unbroken ground plane were chosen. The substrate was a 2 mm thick lossy FR4 layer with relative permittivity 4.35 and conductivity 10^{-3} S/m. Only one trace was excited and terminated (trace 1). The trace was 2 mm wide and both source and load impedances were 50 Ω. The simulations were carried out with an in-house numerical code implementing the finite-difference time-domain (FDTD) method [12].

The number of mesh cell is proportional with $(1/\text{cell size})^3$ and in addition the time step is proportional with cell size. Hence going from 2 mm mesh cells to 1 mm mesh cells increases simulation time 16 times. We chose 2 mm mesh cells and perfectly matched layers as the absorbing boundary condition. The importance of the discretization will be discussed later.

In Method of Moments the effect (shielding, scattering) of Perfect Electric Conductor (PEC) depends much on the on the discretization. In FDTD it is different since the field is forced to be zero inside PEC.

The Huygens' box implementation, i.e. using near-field sources, is still experimental and the code does not yet allow wide band excitation of near-field sources. Hence the HB method is evaluated at frequencies from 20 MHz to 1 GHz, with 20 MHz step and in addition frequencies are added at which resonances occur.

The time step for the cell size of 2 mm was $\Delta t = 3.8483 \cdot 10^{-12}$ s. The majority of the simulations have number of time steps between 30 000 and 100 000, but some of the resonance frequencies required up to several million time steps before the energy criterion was met.

The simulations were carried out on a cluster computer with 24 computers. Each computer contains two Xeon X5650 six core 2.66 GHz CPUs, 145 GB RAM, a 53GB scratch partition, Gbit ethernet and Infiniband interconnect.

With the purpose to increase the credibility of the conclusions, two different boxes were tested in the simulation (Fig. 5 and 6).

Enclosure 1 had the dimension 450 x 300 x 40 mm and was open in one end. The PCB and HB were placed in the middle of the enclosure.

Enclosure 2 had dimensions 500 x 300 x 150 mm, open in both ends and in addition two openings in the top with the size of 100 x 100 mm. The PCB was placed 1 cm above bottom and placed in the space between the holes in the cabinet.

In both cases the simulations were done with and without the galvanic connections to the enclosure (Fig. 6 shows the set-up with galvanic connections).

IV. Results and Discussion

Fig. 7 shows the radiated emission in 3 m distance from the PCB in free space, from the PCB floating inside the enclosure and from the PCB inside and galvanically connected to the enclosure in the corners of the PCB. The simulations were done with input power 1 mW for every 20 MHz and in addition for frequencies where the S-parameter for the full model simulation had resonances. It is clear that maximum radiated emission from the PCB inside the enclosure differs from the free space set-up and that connecting the PCB to the enclosure also has a large effect on the maximum radiated emission. It would be very useful, if it is possible to predict these attenuations and resonances based on the Huygens box method with an uncertainty well below the effect of the enclosure and the connections.

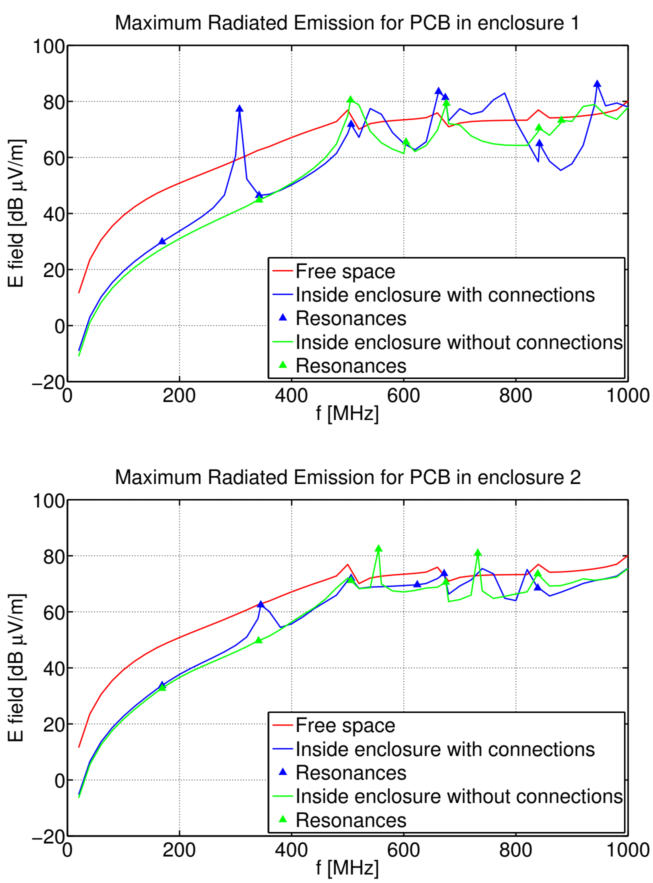

Fig. 7. Maximum radiated emission from the PCB in free space, floating in the box and galvanically connected to the box. Top: Enclosure 1. Bottom: Enclosure 2.

A. *Peak increase for Enclosure 1, PCB not galvanically connected*

Fig. 8 shows the peak increase for the PCB inside enclosure 1 (not galvanically connected to the enclosure). With the purpose of testing the implementation of the HB method in the FDTD code, the peak increase for a free space simulation is also included, i.e. a HB was extracted from a free space simulation and used for a predicting the free space far-field. As expected the peak increase is 0 (black curve coincides with the blue curve).

In Section II.B we stated that including the full model inside the Huygens box restores the fields outside in the presence of obstacles. This is also verified in the figure where the peak increase for HB full model is 0 as expected.

Simulations with HB empty and the ground plane inside HB are almost coinciding, which explains why the red curve is only visible by the markers. The figure shows that including ground plane and substrate makes the peak increase smaller compared to empty HB. The difference between the reference simulation and HB simulation is within ±2 dB when ground plane and substrate are included.

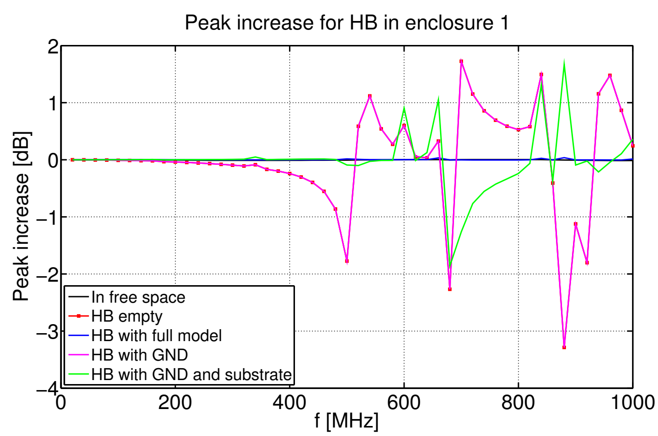

Fig. 8. Peak increase for HB in enclosure 1.

B. *Peak increase for Enclosure 2, PCB not galvanic connected*

Fig. 9 shows the peak increase for HB in enclosure 2. Enclosure 2 is larger and more open than enclosure 1. The difference between the HB and the reference are in general smaller in enclosure 2 compared to the smaller and more closed enclosure 1. The figure shows again that including ground plane and substrate reduces the peak increase compared to an empty HB and HB with just the ground plane. When we included both ground plane and substrate, the difference was below ±1 dB. The importance of including the lossy substrate is clear for the strong resonance frequency 555 MHz.

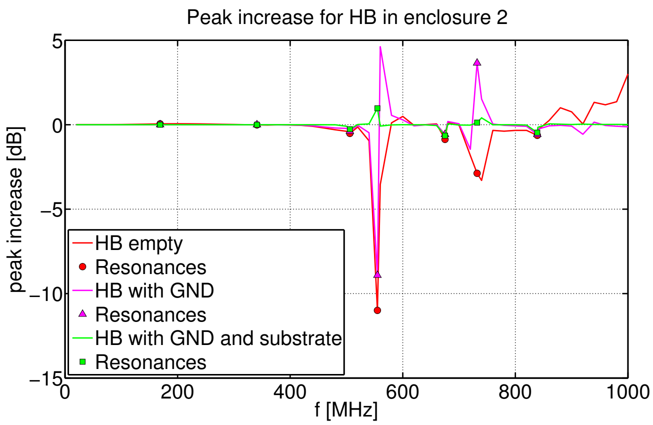

Fig. 9. Peak increase for HB in enclosure 2

C. *Peak increase for PCB galvanically connected in enclosure 2*

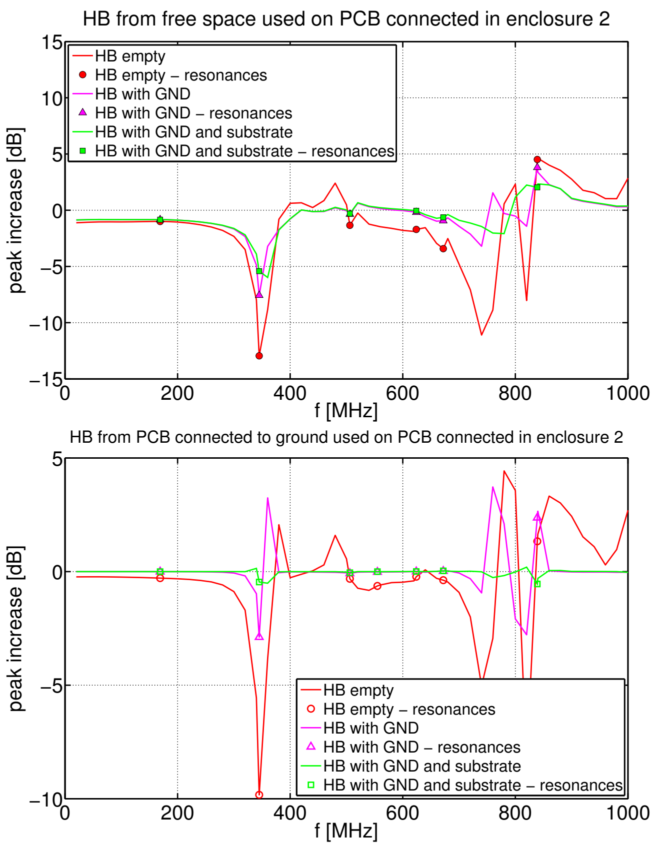

Fig. 10 Peak increase for two different HB's used on a PCB connected to enclosure 2. Top: The HB extracted from free space simulation. Bottom: The HB extracted from a simulation with a PCB connected to an infinite ground plane.

Often PCBs are connected to the chassis. In order to avoid resonances, designers will typical make the connection through a RC circuit. In this paper we made the choice to test the worst case: a 0 Ω galvanic connection to the ground. In Fig. 10 two different approaches for this set-up are compared.

First we used the same HB as in the other simulations, i.e. a HB extracted from a free space simulation. The errors increased compared to the set-up, where the PCB was not connected to the enclosure. Even when the ground plane and the substrate were included, the peak increase was between –6 dB and 2 dB and the large peak increases are present at many frequencies. Fig. 7 shows that the connection to the enclosure caused an increase of the radiation of approximately 10 dB from 340 – 360 MHz, but Fig. 10 shows that this resonance is underestimated by approximately 6 dB if the HB from free space is used.

Then we changed the simulation and used a HB that was extracted from a simulation, where the PCB was connected to an infinite ground plane (Fig. 4). Fig. 10 shows that there were still large errors, if we used the empty HB, but when we included the ground plane and the substrate inside the HB, the error almost disappears, the difference was below ±0.6 dB.

It follows from this experiment, that if a PCB is connected to a metal structure in the product, the PCB must also be connected to a metal structure in the near-field measurements.

D. *Peak increase for different PCB heights*

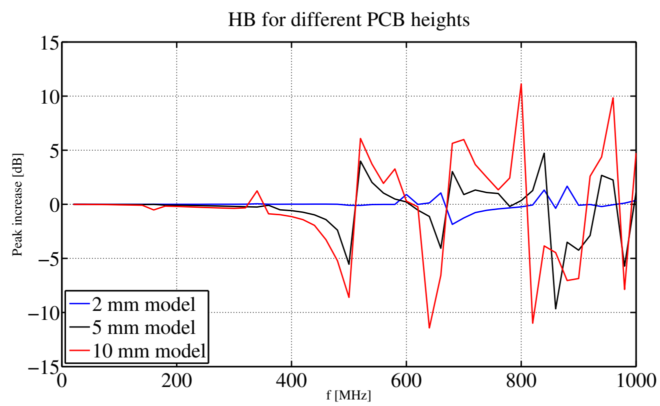

Fig. 11 Peak increase for different PCB heights in enclosure 1.

Until now the suggested method, i.e. to include the most important features in the HB, has been successful. However, the reader may ask: what are the most important features? The ground plane must be responsible for most of the rescattering inside the HB and hence it is expected that including ground plane and the lossy substrate will provide good results.

Another case occurs if the PCB is more complicated and other structures that can rescatter are present. We tried to change the dimensions of the PCB and tested the method on two other PCBs, where the thickness of the substrate and the trace width were changed to 5 mm and 10 mm respectively.

Fig. 11 shows the HB simulation with ground plane and substrate included for the three different heights of the PCB in enclosure 1. It emerges clearly that the higher the PCB the worse the peak increase becomes. The trace, termination, source and ground plane form now a relatively large loop, which can interact with the surroundings. The rescattering from the loop is not taking into account when only the ground plane and substrate is included.

E. The influence of the discretization

In order to ensure that some of the observed differences are not simply the result of insufficient modelling detail, we tried a coarser mesh (10 mm) for the 10 mm high PCB in enclosure 1 (section *D*.) HB simulation with ground plane and substrate included for the two different cell sizes is shown in Fig. 12.

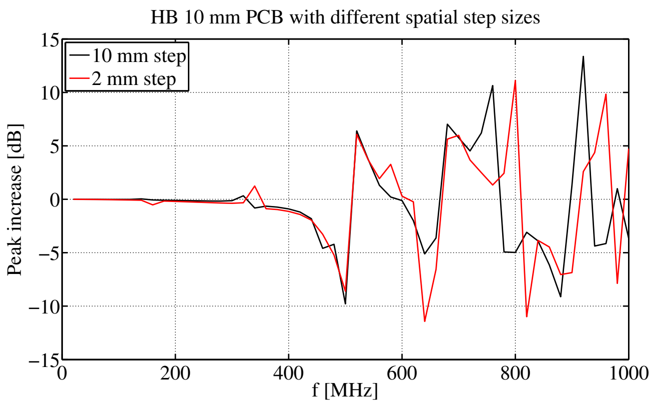

Fig. 12 Peak increase for different spatial step sizes for the 10 mm PCB in enclosure 1.

Going from a fine 2 mm mesh (5 cells across the trace) to a coarse mesh (only 1 cell across the trace and 15 cells across the ground plane) change the "bad" peak increase frequencies but not the overall amplitude.

We also tried a finer mesh (1 mm) for HB in enclosure 1 (section *A*) and in this case a finer mesh caused even worse peak increase for the resonance frequencies compared to 2 mm mesh cell.

V. Conclusion

In this paper, we have compared scenarios of a PCB model inside two different enclosures with similar scenarios where the PCB has been replaced by HB. The comparison was carried out for both the scenario where the PCB was floating inside the enclosure and the scenario where the PCB was galvanic connected to the enclosure.

We have seen that such replacement can cause a significant error in the far-field prediction. However these errors can be reduced by several dB, if main features of the PCB are included in the HB. Best results were obtained if we included both the ground plane and the substrate. Still, if other sources of rescattering, ground plane and substrate may not be sufficient.

If the model of the structure is converging to the full original model, excluding the sources, then the error can be made almost negligible and theoretical zero.

The study also shows that if the PCB is connected to the enclosure, the HB must also be extracted from a simulation/measurement with a ground plane.

It can therefore be concluded, that the HB method may be used as a field source in simulations of PCBs inside enclosures, but only if the main features of the PCB is included in the HB.

If the results can be generalized to other structures and other noise sources, i.e. other kinds of PCBs, the HB method could be a useful precompliance test based on near-field scan and simulations.

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