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PEEC-Models for EMC filter layout optimization

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Abstract

The subject of this paper is related to EMC filter integration. Due to stray interactions between filter components and PCB tracks, or between the components themselves, the transfer function of the filter can be modified. The work will first study these stray interactions and the possible electromagnetic modelling using PEEC method. Then, we aim proposing an automatic procedure to determine the optimal component placement and the associated track design, in order to improve the filter transfer function. Therefore, light models are needed. There will be presented and validated using experimental results.

1 Introduction

Integration in power electronics, leads to reduce distances between the converter components. On the EMC Filter point of view, which represents usually 30% of the converter volume, the efforts of integration are especially needed. Therefore, strong interactions can be encountered, between filter components and circuit tracks, or between the components themselves. Some authors have already experienced and reported these phenomena in the literature [1], and even proposed some guidelines for component placement and the associated layout [2]. This work proposes some models to better analyse these stray interactions, based on PEEC method. Going further than "simply" avoiding interactions as in [2], we would like to be able to use them, as in [3] or [4] for instance. Therefore, suitable models have to be proposed, needing less computation time.

2 Use of PEEC models for filter components

2.1 Advantage of PEEC modeling method

PEEC method is an integral method allowing solving electromagnetic problems by meshing the conductors only, and not the air around [5-6]. Therefore, it is very interesting to handle the complex 3D geometries encountered in power Electronics, as the power modules for instance [7].

Up to now, it has been especially used to model the interconnects, but we would like to use it also to handle the passive components stray electromagnetic behaviour. Indeed, it would allow obtaining all stray couplings between the components and the tracks in a single complete electromagnetic model, using a very powerful quick method. Obviously, some simplifications of the component geometry have to be done, and the objective is to focus on the stray behaviour of the inductive and capacitive components only.

2.2 Use of PEEC modelling method for Capacitors

2.2.1 "Physical" model

On a magnetic point of view, a capacitor is only made of several thousands of layers of metallization. It is obviously not possible to describe the exact internal geometry with all the thin film layers. Therefore, a homogenization technique has been used, associated to a simplified geometry (Figure 1). Like Dowell method [8] the resistivity is adapted. Five electrodes allow accounting for the current division inside the lateral metallization and the heart of component. This number of electrodes results from a trade off between the physical possibility of current division among several paths and a limited increase of the geometrical complexity.

The extremities of the electrodes are connected using perfect equipotentials. This model accounts therefore for the capacitor magnetic behaviour only, and has to be completed with a series capacitance.

The magnetic behaviour of this equivalent components is thus supposed to provide the Equivalent Series resistance (esr), the Equivalent Series inductance (esl) and of the capacitor *and the associated magnetic couplings* with the surrounding environment (other components and tracks). Thus, the model calibration will be achieved on the EsL and esr values. As illustrated in Figure 1, the model has three degrees of freedom which have been used to fit some experimental measurements on a particular capacitor reference. These three parameters are the homogenised resistivity and the thickness of the equivalent electrodes, and the spacing between them.

Ten 680nF plastic capacitor have been measured successively on an impedance measurement bridge to obtain the esr and esl. The average C value is 640nF. The average esl is 9.4 nH, with a very small variation of some %. The average esr at 10 kHz is 21.6 mΩ, with a 10% variation. These values have been chosen to calibrate the model. Figure 1 shows the impact of the three model parameters on the esl (with a given value of electrode spacing k,

which has been adjusted using the esl value).

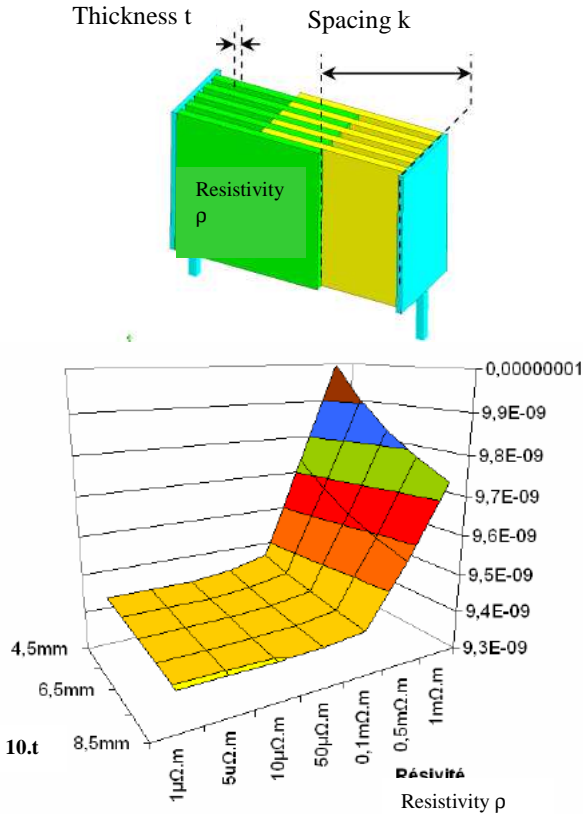


Figure 1 The proposed PEEC model for a capacitor and the parameters adjustments to fit the esl.

The identification results in:

$$\begin{aligned} \rho &= 7.3 \cdot 10^{-5} \Omega \cdot m \\ k &= 8.125 \text{ mm} \\ t &= 0.85 \text{ mm} \end{aligned}$$

The rest of the geometry is fixed by the actual component size.

The model validation has been achieved using the experiment illustrated in Figure 2. Two identical 680nF capacitors (actual value measured 640nF) have been associated in parallel on a simple PCB. The relative positions of the capacitors are variable. Close together, the magnetic coupling is obviously greater than for the extreme position where the capacitors are far away. The impedance measurement of this association is illustrated in Figure 3, and Figure 5 shows the comparison of the PEEC model of the association with the measurement, for the position where the capacitors are close. The matching is also good for the other positions. To be noticed that in this approach, all impedances and couplings are taken into account: tracks impedances and associated couplings, coupling between components, and with the tracks. The equivalent inductance that would be obtained without all these couplings would be 15.8 nH (accounting for the two paralleled esl and all tracks inductances). The simulation (and experi-

mental results) gives 12.6 nH. The 3.2 nH difference corresponds thus to the influence of all couplings, between components and between tracks and components. This is not negligible, and the good agreement between the model and the measurements validates the proposal.

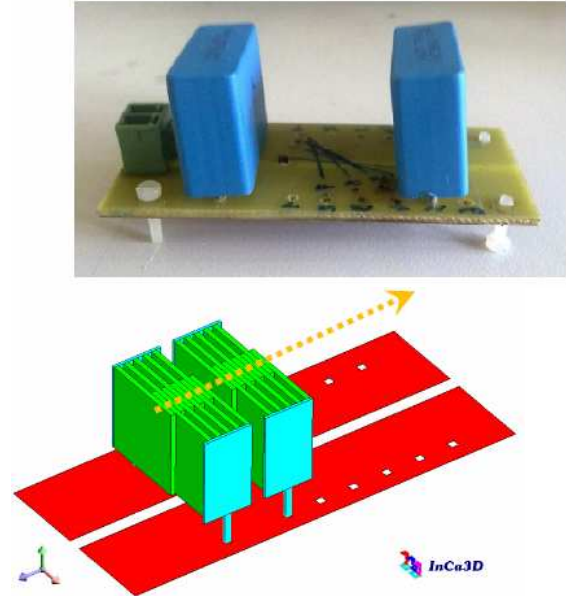


Figure 2 Experimental setup to validate the model: association of two capacitors in parallel.

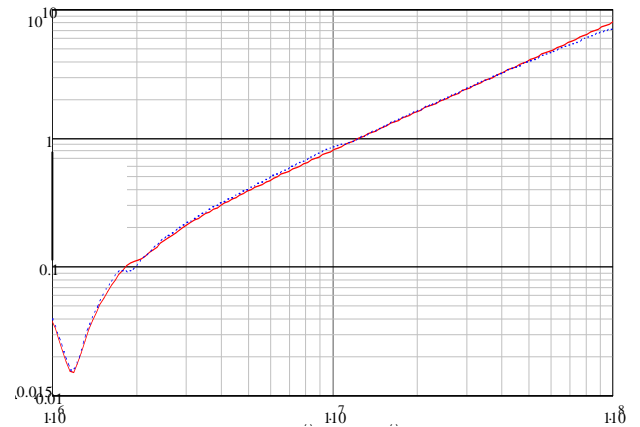


Figure 3 Impedance of the parallel association of the two capacitors close from each other: comparison between simulated (solid line) and measured (dot line) values.

2.2.2 Simplified model

Even if the previous model is a simplification regarding the actual capacitor geometry, it is still complex and generates large PEEC model size. Furthermore, the equivalent electrode thickness t impacts not so much the result, as shown in Figure 1. Another model has thus been proposed, somewhat less accurate but very simple, in order to reproduce the magnetic stray coupling (Figure 4).

A single electrode is used, linked with a perfect equipotential to the lateral metallization. The current is forced to circulate along the single electrode, and thus the representation is less "physical" than in the actual component. However, the results are still fair regarding the magnetic behaviour, in comparison with the previous model.

The equivalent resistivity ρ and the spacing k are used to fit both esl and esr (k stays obviously below the capacitor size).

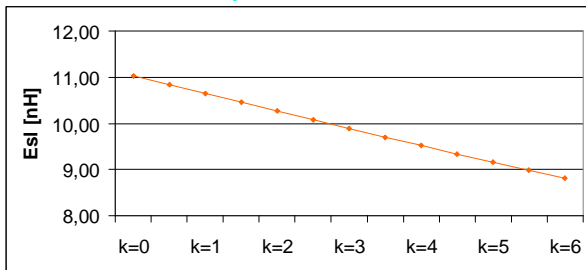
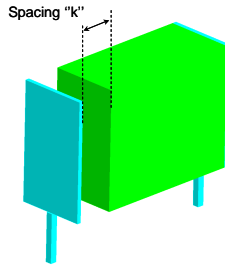


Figure 4 A simplified model of the capacitor and the k spacing influence.

Using $\rho = 1.25 \cdot 10^{-4} \Omega \cdot m$ and $k = 4.5 \text{ mm}$ leads to $esl = 9.37 \text{ nH}$ and $esr = 20.9 \text{ m}\Omega$ at 10 kHz . The model validation has been carried out using the same application as previously. Figure 5 shows the comparison between the model and the experimental result for a special position, where the two capacitors are the closest. The results are still good, what is reasonable in comparison with the previous model. The equivalent inductance that can be seen in the high frequency range is 13.0 nH , in comparison with the 12.6 nH of the previous model and measurement.

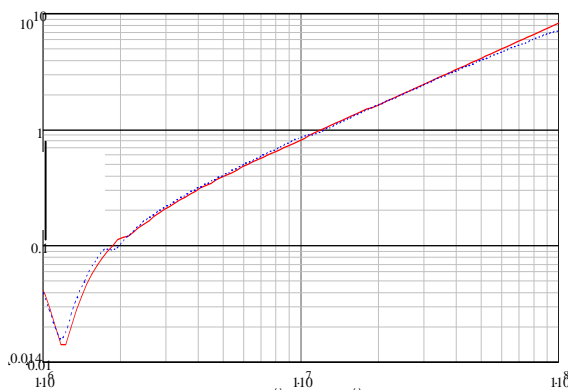


Figure 5 Capacitor parallel association (close together). Impedance measurement (dot) and simulation (solid) using the simplified model.

2.3 Use of PEEC modelling method for Inductors

2.3.1 Actual description of the geometry

PEEC method does not allow, up to now, to handle non homogeneous magnetic medium, even if some works have proposed interesting methods [9], [10].

Fortunately, the stray magnetic field is very few dependent of the presence of the magnetic material, as used in [11] and illustrated in this paper. Therefore, a PEEC model based on the conductors description only can be proposed. Obviously, it will not be able to represent the full inductive behaviour, and it will be necessary to complete it by a series inductor, in order to account for the effect of the magnetic material. However, the stray magnetic field will be accurately represented by this method.

Several experiments have been achieved using toroidal inductors associated with different materials: one Plexiglas non magnetic core, and a iron powder one (Figure 6). Two different windings have also been used, in order to check the validity of the assumption on a non uniform winding. PEEC simulations have been carried out using the description of the winding geometry. In order to check the ability of the model to reproduce the coupling, the inductor has been located near a test loop. The voltage induced in this loop defines the mutual coupling between the inductor and the environment. This experiment is illustrated in Figure 7.

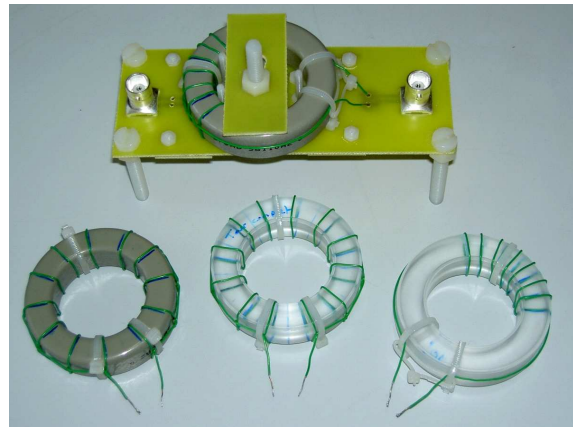


Figure 6 Different toroidal inductors using two materials and two windings shapes.

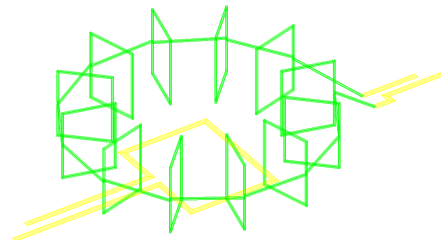


Figure 7 Test configuration to check the mutual coupling between the inductor and the environment.

All kinds of windings and materials have been tested. The results are summarized in table 1. It is clear that the presence of the magnetic material has no impact on the mutual coupling, even for non homogeneous windings. From Table 1, it can be also seen that the proposed model is fairly good. The 10% difference with measurement can easily be explained by measurement inaccuracies, and some mistakes in the winding description for the simulations.

Table 1 Identification of the mutual coupling with the environment.

Experimental results [nH]			Simulation[nH]
Material	Iron Powder	Plexiglass	None
Full winding	10,8	10,9	9.8
Quarter turn winding	11,1	11,6	10.4

2.3.2 Model simplification

However, as for the capacitor, the previous model is too heavy to be used in an optimization process. Therefore, further simplifications have been proposed. A simple loop has been used to replace the full winding, as illustrated in Figure 8. It generates the same field around the component, even if obviously, the field inside the wiring is no more represented. However, this field contributes to the inductor value only, which is not necessary since the model must be completed with a series inductor, as mentioned previously.

Table 2 summarize the different results obtained with this simplified model. Even if the accuracy is reduced in comparison with the geometrical modelling, the concordance is still good, and the computation times are reduced dramatically. The effect of the equivalent loop position regarding the core geometry has also been studied. The best position is located in the center of the core. For the example of a full winding, a disposition on the top of the core would result in a too low mutual inductance (6.4 nH), whereas on the bottom, the mutual would reach 15.8 nH, what is too high in comparison with measurement.

Finally, several other dispositions of the test loop have been checked, using the experimental system of Figure 9 and all results match pretty well the simulations of both complete and simplified model.

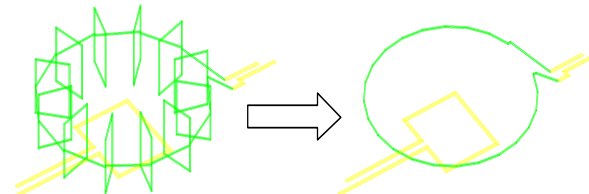


Figure 8 Test configuration to check the mutual coupling between the inductor and the environment: Left complete PEEC model for an inductor to represent the mutual couplings with the PCB tracks. Right simplified model.

Table 2 Identification of the mutual coupling with the environment for the simplified model.

Experimental results [nH]			Simulation[nH]
Material	Iron Powder	Plexiglass	None
Full winding	10,8	10,9	9.9
Quarter turn winding	11,1	11,6	9.8

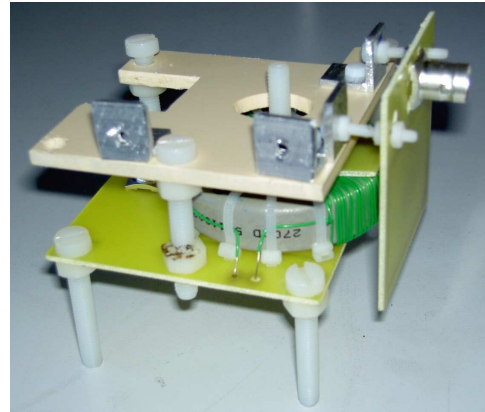


Figure 8 Test configuration for other disposition of the sensor loop.

3 Models validation in a full filter

The final validation of the proposed models is to use them in a full filter, and to check various layouts. A simple differential mode filter has been used for this purpose, composed of a differential mode inductor (46.3μH) and two Cx capacitors (the ones identified in section 2). The different layouts are summarized in Figure 9. The chosen configurations intend to maximize or minimize the couplings in order to investigate a large panel of solutions. To check the validity of the models used, each simulation has been compared with measurement. Impedance measurement as used in the previous section is not completely suitable for checking the model accuracy, since the stray couplings do not impact the input or output impedance significantly. Therefore, we used a network analyzer, to obtain the filter transfer function, by measuring the scattering matrix ("S parameters"). Figure 10 illustrates the difference of using the input impedance and the transfer function in the case of the considered differential mode filter, accounting for a simple magnetic coupling between the two capacitors of 0nH, 2nH or 4nH. It is clear that the transfer function is more appropriate.

From the comparison of Figure 11, between all the cases and the measurement, it is clear that the complete models provide a good correspondence with measurement, and that the simplified models are sufficient to account for stray couplings in an optimization process, with limited computation times in comparison with the "full" models.

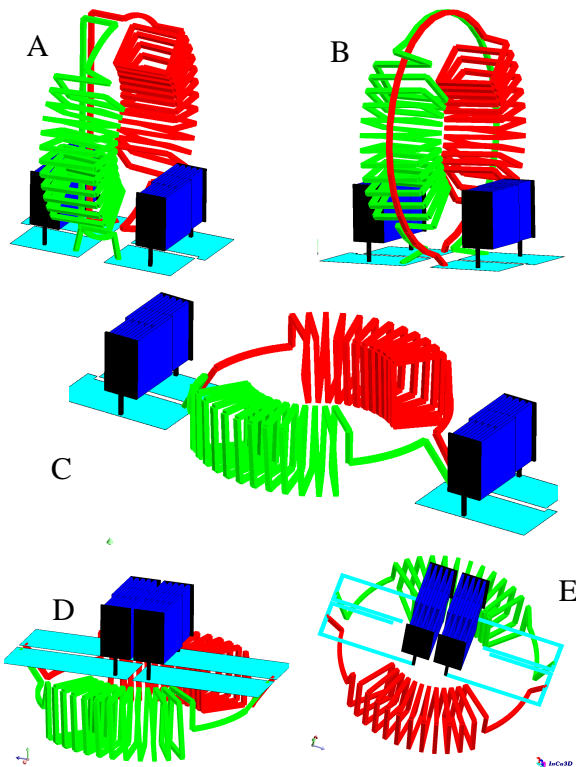


Figure 9 The different layouts used in the validation. A) Standard – B) Max coupling between components C) Min coupling between components - D) Min coupling between components – E) Max coupling with the tracks

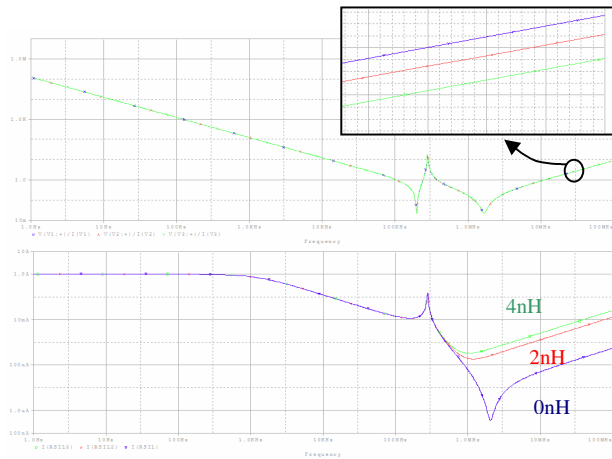


Figure 10 Impact of a stray coupling between the Cx capacitors on the EMC Filter transfer function and on the input impedance.

4 Use of models for Hierarchical Sorting of Couplings

Among all the possible couplings involved in a EMC filter, we have listed the component to component and the component to track couplings. The proposed models are

suitable to account for all these couplings, even in the simplified version, dedicated for optimization; however, another interesting application of the simulation is to allow differentiating all couplings, in order to investigate the most influent.

To achieve this task, the components have been disposed at a very high distance of the tracks (1 meter), but still linked to the PCB tracks using perfect equipotentials. Therefore, the coupling with the track becomes negligible. In this case, the transfer function becomes very close to the simulation without couplings. On the other hand, we can localize the components far away from each one, in order to reduce the component to component couplings. However, the track to component coupling is still present and the transfer function is still different from the simulation without coupling;

Therefore, it can be concluded that the most important stray couplings are the component to tracks ones.

5 Conclusion

The originality of this paper was not to illustrate the impact of stray coupling on the EMC filter transfer function, since this has already been investigated by several authors. The first contribution is to sort these stray couplings by hierarchical importance (component-track coupling impacts more the transfer function than component to component coupling). The second contribution is to propose PEEC models to investigate the coupling. Complete models are presented, as well as optimization models, which will allow a real optimization of the EMC filter layout. Going further than previous work, it will be possible not only to avoid couplings, but also to use them, in a full optimization procedure.

6 Literature

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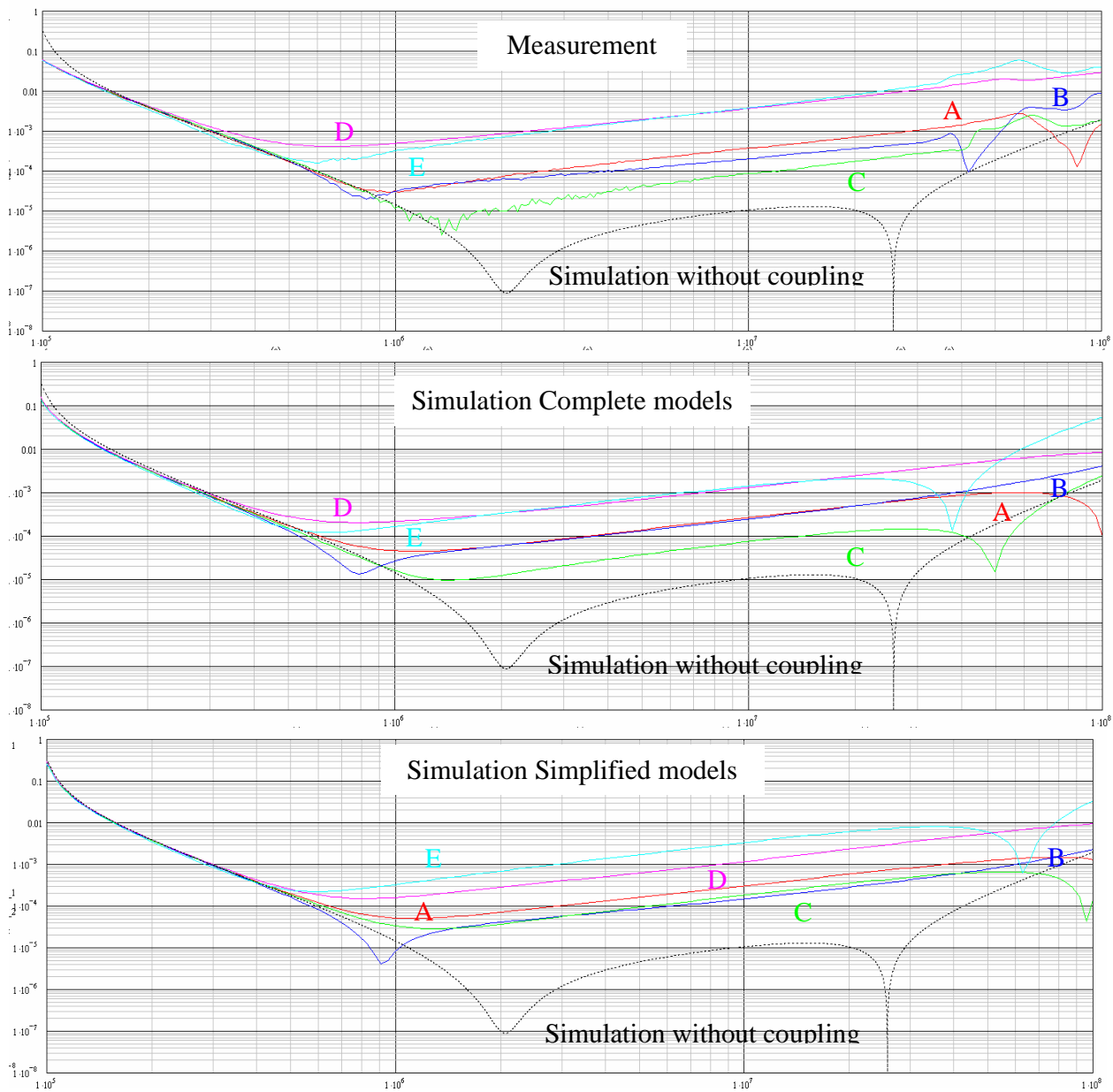


Figure 11 Various layout of DM filter. Comparison of experimental results, complete and simplified models.

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