# Novel Efficient Strategy to Design an Optimized Microwave Shield

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**The purpose of this work is to provide a novel systematic approach to design efficiently a microwave shield for household appliances, required for EM radiation safety. In this work, a FEM software has been used to simulate and quantify the EM quantities. The strategy is based on the creation of a reduced model of the device, in order to achieve less computational complexity. The reduced and the full models are characterized by different response functions, which are compared using a numerical criterion to guarantee consistency between the models. During the process, a parametric sweep analysis or/and an algorithmic optimization can be applied to achieve the desired EM performances. Experimental validation of the numerical results has been also derived.**

***Index Terms*—Design methodology, Microwave devices, Microwave propagation, Radiation safety.**

## I. INTRODUCTION

THE DEVELOPMENT of devices capable to shield high frequency electromagnetic radiation begun in the period of the 2nd World War. The first patent of the so-called "choke" has been made in 1950, and the first paper was published in 1956 [1]. From that period on, many other publications and patents have been derived thanks to the unstoppable improvement of the computer performances and appropriate simulation codes. Little by little, the Shielding Effect (SE) has been increased during the last decade because there is a higher sensitivity for EM compatibility and safety issues. An in-depth study of the thermal effects caused by the exposure to a microwave oven can be found in [2], also induced thermal effect inside the human body, due to EM radiation is analyzed in [3]. The periodical slot structure represents the most important shielding characteristic. Therefore, the slot and the periodic element "teeth" have to be defined to achieve the minimization of the leakage. Many brilliant solutions have been already studied and analyzed by researchers as in [4]-[5]. International and regional law requirements, mainly due to health reasons, can determine specific conditions to the final design. Therefore, a general numerical strategy has been developed in this paper in order to satisfy generic design-needs, but with particular attention to the reduction of computational complexity due to the intense use of simulations.

## II. DESIGN PROCESS AS A FORMAL PROBLEM

Let us assume that we want to design a device, whose performances are maximized when a functional $y$ is made as small as possible. The purpose of this section is to define the numerical design-steps in a formal way. The device is characterized by a series of parameters $\boldsymbol{x} = [x_1 \ldots x_n]$ with the design constraints $\boldsymbol{x}_{min} = [x_{\min 1} \ldots x_{\min n}]$ and $\boldsymbol{x}_{max} = [x_{\max 1} \ldots x_{\max n}]$. The choice of $\boldsymbol{x}$ is fundamental also for the computational complexity. The domain of the analysis is defined by a series of intervals $\mathcal{D}_j = [d_{\min j} \ldots d_{\max j}]$ where $j = 1 \ldots m$, while $\Delta d_j$ is the analysis domain step and $\boldsymbol{d} = [d_1 \ldots d_m]$ is the domain vector.

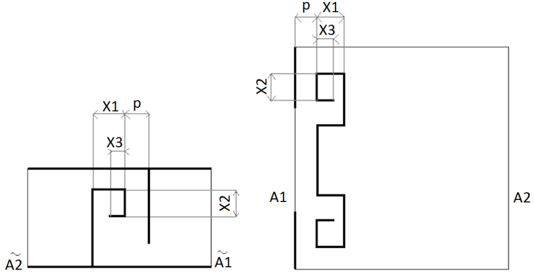

Fig. 1. 2D-view schema of the reduced and full model of the systems.

The central vectors of the considered system are $\boldsymbol{x}_0$ and $\boldsymbol{d}_0$. The influence of $\boldsymbol{x}$ on the physical quantity $y$ is evaluated through the scalar function $h: \mathbb{R}^{n+m} \to \mathbb{R}$, $y = h(\boldsymbol{x}, \boldsymbol{d})$. The proposed method is based on a preliminary assessment to create a sensitivity chart of the scalar components of $\boldsymbol{x}$ in four steps as presented in Table I.

TABLE I
SENSITIVITY CHART COMPUTATION

| Action | Object | Condition | Note |
|---|---|---|---|
| evaluate | $H^j(\boldsymbol{x}_j, \boldsymbol{d}) = h^j(\boldsymbol{x}_{0j}, \boldsymbol{d})$ | $\boldsymbol{x}_{0j} = \boldsymbol{x}_0$ | $\boldsymbol{x}_{0j}(j)$ is free |
| find | $H^j_{max}, H^j_{min}, \langle H^j \rangle$ | - | - |
| compute | $C^j = (H^j_{max} - H^j_{min})/\langle H^j_{max} \rangle$ | - | - |
| sort | $C^j$ | - | high → low |

This computational procedure has to be performed with $j = 1, \ldots, m$.

Once the model has been defined we have to create a simpler and a more compact model, which has to maintain a similar physical behavior of the previous one. The new model can be mathematically represented by $\tilde{y} = \tilde{h}(\boldsymbol{x}, \boldsymbol{d})$. It has to be stated that the reduced model has to satisfy a correlation condition that can be computed in three steps as presented in Table II.

TABLE II
CORRELATION CONDITION

| Action | Object | Condition | note |
|---|---|---|---|
| evaluate | $\nabla h = \left[\frac{\partial h}{\partial x_1} \ldots \frac{\partial h}{\partial x_n}\right], \nabla \tilde{h} = \left[\frac{\partial \tilde{h}}{\partial x_1} \ldots \frac{\partial \tilde{h}}{\partial x_n}\right]$ | $\begin{cases} \boldsymbol{x} = \boldsymbol{x}_0 \\ \boldsymbol{d} = \boldsymbol{d}_0 \end{cases}$ | - |
| compute | $\boldsymbol{J_1} = sgn(\nabla h),\ \boldsymbol{J_2} = sgn(\nabla \tilde{h})$ | - | - |
| check if | $\boldsymbol{J_1} = \boldsymbol{J_2}$ | - | ⇒ ok |

The consistency between the models can be verified with this procedure.

When the correlation condition is satisfied, a parametrical sweep analysis or an algorithmic optimizer, as deeply and extensively described in [6], can be applied to the reduced model. The parametric sweep analysis could be more intensive from a computational point of view and less effective from the standpoint of performances, with respect to the optimizer. An optimal solution $\tilde{x}_*$ of the simple model can be obtained, and it has to be applied to create a full model of the device. This full model should be actually close to an optimum final design $\boldsymbol{x}_*$ which can be reached by a final low-cost computation similarly to the previous computation.

## III. Implementation of the Model

In Fig. 1 we observe the 2D-views of the 3D reduced and full models. The first one is characterized by an EM power input $P_1 = 2000$ W crossing the input area $\widetilde{A_1}$. The leakage is represented by $P_2$, going out from the surface $\widetilde{A_2}$. The selected response function (numerically assessed using FEM solvers) is $\tilde{y} = \widetilde{S_{21}} = \sqrt{P_2/P_1}$ which physically represents the scattering parameter between port 1 and 2. The reduced computational domain is $\widetilde{\Omega}$, while the full model is defined in $\Omega$. $P_1$is the input power and the value of $y$ can be computed as follows

$$y = \sqrt{\left[\int_{A2} Re(\bar{\mathbf{E}}\times\bar{\mathbf{H}}^*)\cdot\hat{n}\, dA\right]/P_1} \qquad (1)$$

The other parameters of the analysis have been set as: $\boldsymbol{x} = [x_1, x_2, x_3]$, $\boldsymbol{x}_{min} = [30,30,5]$mm, $\boldsymbol{x}_{max} = [50,50,15]$mm, $\boldsymbol{x}_0 = [35,40,10]$mm, $f = d_1 \in \mathcal{D}_1 = [902, 928]$ MHz, $p = d_2 \in \mathcal{D}_2 = [3,5]$mm, $\Delta d_1 = 2$MHz, $\Delta d_2 = 1$mm. The computed results, applying FEM techniques are $\nabla\tilde{h} = [-3.888, -1.501, -2.88] \rightarrow \boldsymbol{J}_1 = [-1, -1, -1]$, and $\nabla h = [-8.19, -4.418, -10.912] \rightarrow \boldsymbol{J}_2 = [-1, -1, -1]$, therefore the correlation condition is satisfied. The computed sensitivity chart is presented in Table III:

TABLE III

COMPUTED SENSITIVITY CHART FOR THE DESIGN VARIABLES

| $j$ | $S_{21\,min}$ | $S_{21\,max}$ | $\langle S_{21}\rangle$ | $C^j$ |
|---|---|---|---|---|
| 1 | 3.98E-5 | 2.09E-8 | 8.19E-7 | 3.32 |
| 2 | 1.43E-1 | 1.24E-1 | 6.14E-2 | 4.15 |
| 3 | 4.30E-2 | 2.99E-2 | 1.53E-2 | 4.02 |

The appearing values derive from a preliminary parametric analysis to assess the impact on the scattering parameter for each design variable $x_j$.

We can observe that the design variables have the same order of magnitude ($C^1 \backsimeq C^2 \backsimeq C^3$). Therefore, none of them can be neglected.

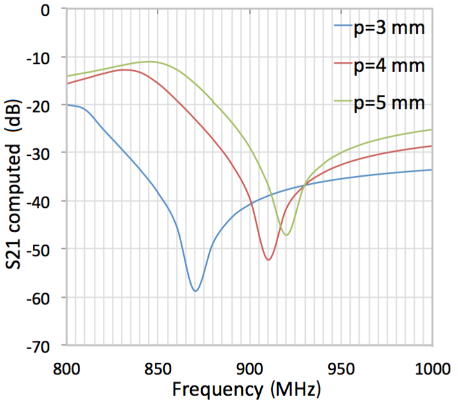

Fig. 2. Objective function over the frequency domain, parameterized by different values of p. The computation is made using FEM software.

Finally, after a parametrical sweep optimization (in this phase an Evolution Strategy can be applied), we have obtained the set of design variables $\tilde{\boldsymbol{x}}_* = [26,30,5]$mm, and the final close solution for the full model $\boldsymbol{x}_* = [30,28,6]$mm. In Fig. 2 the objective function has been reported, over the domain analysis $\mathcal{D}_1$ and $\mathcal{D}_2$. Over the entire analysis domain $S_{21\,db} < -20 \Rightarrow \mathrm{SE} > 99\%$.

## IV. Conclusion: EMI Testing and Validation

In order to confirm the design and simulations, testing must be performed. A method that will give indications that the Device Under Test (DUT) will pass requirements at a 3 or 10 meter range is to fabricate a compact range. The compact range must be large enough to measure only farfields. The range must also be lined with absorbing material to attenuate reflections so only the “line of sight” measurements are made. Measurements can be conducted with a network analyzer to determine the attenuation or gain of the DUT or a signal generator/spectrum analyzer combination. The receive antenna is a wideband double ridge waveguide horn for frequencies > 1 GHz and up to 18 GHz. For receive antennas making measurements at frequencies < 1 GHz patch antennas have been utilized, which are very space efficient. The experimental measurements presented in Fig.3 are compatible with the computed results, confirming the effectivness of the computational strategy based on the reduced model analysis.

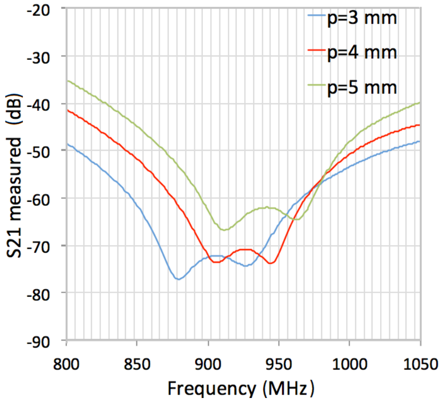

Fig. 3. Experimental measurements obtained in the laboratory to verify the actual values of the scattering parameters over the analysis domain.

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