

## Research Article

# The Multi-Field-Coupled Model and Optimization of Absorbing Material's Position and Size of Electronic Equipments

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There are three fields in electronic equipment such as structure deformation (S), temperature (T), and electromagnetic (EM) fields. Both deformation and temperature will affect the electromagnetic shielding performance of the equipment considerably, particularly in the case of enclosure with small volume and high packaging density. Because the position of electronic device and the shape of outlet will be changed with structural deformation, there must be therefore an adherent relationship among three fields. To begin with, this paper presents a three-field-coupled model called STEM. Then, to enhance the capability of electromagnetic shielding of the equipment, an efficient way is to attach absorbing material to the inside of it. Under the condition of pre-given material characteristics itself, the position and size of absorbing material are of significant effort on electromagnetic shielding. The optimization model based on STEM is developed in this paper. Next, the numerical and practical experiments of an actual enclosure are given to demonstrate the feasibility and validity of the model and methodology.

## 1. Introduction

There are two main approaches used in electromagnetic shielding of electronic equipment, reflecting and absorbing. The former makes use of characteristics of good conductor that can reflect electromagnetic wave and restrict the energy in a specific space. However, the energy will not be transformed efficiently. In this case, electronic field of some space is decreased and one of others will be increased. The worst case is led to resonance.

As an efficient way of absorbing shielding, the attachment of absorbing materials is widely utilized. Microwave absorbing material, which is the basic material of modern aircraft and weapon, support the modern stealthy technique. Since World War II, that had been focused by the defense of each country. At present, absorbing material is used in EMC to simulate semifree and free space in a half-wave and full-wave darkroom. The application is successful [1].

In addition, there are some other areas' applications, such as eliminating the resonance of cave, reducing interference between circuits, highlighting the stability of circuit, and enhancing the shielding efficiency of enclosure. However,

most of researches depended upon engineer experience. Few researches are concerned quantitative application of absorbing material to suppress the electromagnetic interference. In 1988, Dawson and Marvin [2] presented method on restrain of the cave's resonance by utilizing absorbing material. Henceforth, some scholars [3] are followed.

The shielding doors with big shielding space need to be opened frequently for the purpose of being in and out of people and material. When the shielding doors open, the continuous of electroconductivity is broken, and which leads to the decrease of shielding efficiency. Hence, the dual interlocking shielding doors are adopted in lots of shielding spaces, which can make sure that the electro-conductivity is continuous whenever only one door is opened. This approach keeps the shielding efficiency high, but the effect is poor. Sometimes, the apertures of equipment (such as the feed slot of printers, scanners, and copy machines) are unavoidable, and it is impossible to use the shielding door. For the sake of this, Mauriello [4] submits a purposely study on restraining the electromagnetic leakage with labyrinth and absorbing material by means of model test and numerical simulation.

However, little of the above research considers the optimal position and size of the absorbing material. This paper intends to do it, that is, to search for the optimal value of EMC shielding performance whilst satisfying the constraints of volume, temperature, nonoverlap between the absorbing material by selecting the position and size of materials. This paper will discuss this in detail.

## 2. The Coupled Model among Electromagnetic, Temperature, and Structural Fields

As shown in Figure 1, under load  $P_1$  and  $P_2$  and vibration of the base, the chamber will be deformed. As a result, the outlet configuration at the top and front plane will be changed. It further leads to the change of not only boundary of temperature and electromagnetic fields, but also the position of electromagnetic radiate devices ( $v_i$  and  $v_j$ ) and ventilation window. Besides, the increase of temperature results in decrease of performance of radiate devices. At the right plane, three holes are for the fans to reduce the temperature in the enclosure.

According to the definition of electromagnetic compatibility (EMC), the relationship between  $EMCS_E$ , deformation increment  $\Delta\delta$ , and temperature  $T$  can be written as follows:

$$S_E = 20 \log \frac{\sum_{i=1}^{nem} E_i^0(\delta^0)}{\sum_{i=1}^{nem} E_i[(\delta^0 + \Delta\delta(\mathbf{P}, \mathbf{T})), \mathbf{V}(\mathbf{T})]}, \quad (1)$$

in which  $nem$  is the total number of radiate devices within the enclosure, so we have the vector  $\mathbf{V} = (v_1, v_2, \dots, v_{nem})^T$ , that is the function of temperature. Theoretical figuration of enclosure is denoted with  $\delta^0$ . The deformation increment due to external load, vibration and thermo is described with  $\Delta\delta$ . The electromagnetic strength at the considering position without and with enclosure is shown by  $E_i^0$  and  $E_i$ , respectively.

The vectors of deformation  $\delta$ , load  $\mathbf{P}$  and temperature  $\mathbf{T}$  are subject to the following equations,

$$\mathbf{M}\ddot{\delta} + \mathbf{C}\dot{\delta} + \mathbf{K}\delta = \mathbf{P},$$

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \eta \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \eta \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \eta \frac{\partial T}{\partial z} \right) + q_v. \quad (2)$$

In which,  $\mathbf{M}$ ,  $\mathbf{C}$  and  $\mathbf{K}$  are, respectively, the mass matrix, damp matrix and stiffness matrix.  $\delta$ ,  $\dot{\delta}$  and  $\ddot{\delta}$  are, separately, displacement, velocity and acceleration vectors of the structure finite element nodes.  $\mathbf{P}$  is the external loading vector.  $\rho$  is the fluid density,  $\eta$  the thermal conduct efficiency,  $c_p$  the specific heat at constant pressure and  $q_v$  the strength of heat resource.

Corresponding to numerical computation of three fields, finite element model of structure is produced at first and the displacement can be known by finite element method, then temperature field and electromagnetic field can be found by finite volume method (FVM) and method of moment (MOM).

The procedure of numerical computation can be stated as follows.

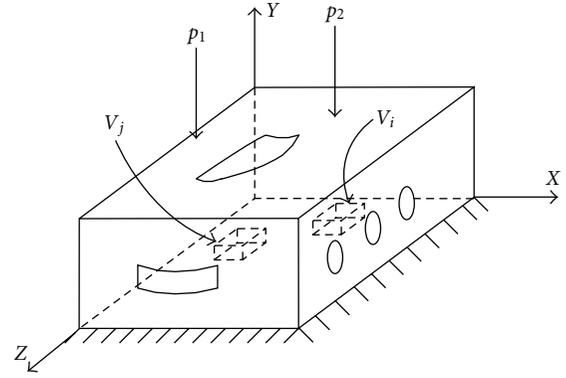


FIGURE 1: Sketch of STEM in electronic equipment.

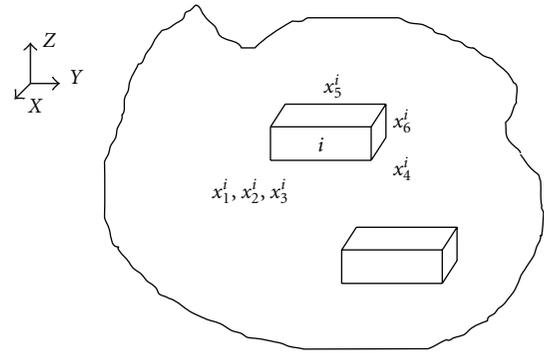


FIGURE 2: Sketch map of attaching absorbing material.

- Establishing the mesh model  $\Gamma_1$  for structural deformation field, model  $\Gamma_2$  for temperature field and  $\Gamma_3$  for electromagnetic field. Generally speaking, the mesh size (for instance, side length of triangular element) in model  $\Gamma_3$  is approximately  $\lambda/8$ ,  $\lambda$  is wavelength the mesh size (distance between two node of FVM) in model  $\Gamma_2$  is subjected to  $P_e \leq 2$ , in which  $P_e = \rho u \Delta x / \Gamma$ . Where  $\rho$  is fluid density,  $u$  fluid speed in  $x$  coordinate,  $\Delta x$  distance between two nodes along  $x$ -coordinate, and  $\Gamma$  diffusion coefficient.
- The displacement of structural finite element node can be obtained under the given load. The node position in  $\Gamma_2$  and  $\Gamma_3$  is known from projection matrix.
- The electromagnetic strength and temperature can be known by MOM and FVM, respectively.

## 3. Mathematical Description of Optimization Design Problem

As mentioned previously, analysis of electronic equipment refers to electric field (magnetic field) in and out of equipment, temperature distribution in the equipment, and its deformation (when applying external load). Electric field (magnetic field) and temperature distribution will be affected by deformation as the boundary conditions are changed. This paper tries to investigate how the position and

size of absorbing material attached in electronic equipment affect the electromagnetic shielding efficiency, under the condition of satisfying temperature distribution requirement.

**3.1. Design Variable.** In Figure 2, it is supposed that  $n$  pieces of absorbing material are attached to the inside of enclosure, each of which is described with six parameters. Generally speaking, take the  $i$ th piece as an example,  $x_1^i$ ,  $x_2^i$ , and  $x_3^i$  denote the central position, and  $x_4^i$ ,  $x_5^i$ , and  $x_6^i$  denote length, width and thickness, respectively. For  $n$  pieces of absorbing materials, design variable can be represented uniformly as follows:

$$x = (x_1^1, x_2^1 \cdots x_6^1 \cdots x_1^n \cdots x_6^n)^T, \quad 1 \leq i \leq n, \quad 1 \leq j \leq 6. \quad (3)$$

**3.2. Objective Function.** The purpose of attaching absorbing material is to, efficiently, suppress the resonance in cave. One purpose of optimization is to minimize the maximum coupling degree between two probes at the certain frequency and mode, and meanwhile considering leakage of the cave. The other purpose is to minimize the maximum electromagnetic-field intensity that is calculated at the position at one meter away (the position of one meter away is from the Chinese standard for design of electronic equipment,) from the center of maximum leakage plane. Thus, the objective function can be described as

$$f(x) = \alpha_1 C_{\max}(x) + \alpha_2 E_{\max}(x), \quad (4)$$

where  $\alpha_1$  and  $\alpha_2$  are weight factors.  $C_{\max}(x)$  is the maximum coupling degree among different modules. Its mathematical expression is as follows:

$$C_{\max}(x) = \max \left\{ 10 \log \left[ \frac{P_{\text{in}}^i(x)}{P_{\text{out}}^j} \right], i, j = 1, 2, \dots, \text{num}; i \neq j \right\}, \quad (5)$$

in which num is the total number of radiation and sensitive devices in enclosure.  $P_{\text{in}}^i(x)$  is the received power of the  $i$ th device from the  $j$ th radiation device, which will be influenced with deformation that is function of variable  $x$ .  $P_{\text{out}}^j$  is the radiated power of the  $j$ th device.  $E_{\max}(x)$  is the maximum field intensity, calculated at the position at one meter away from the center of the maximum leakage plane.

**3.3. Constrained Function.** During optimization, there is requirement about the sizes of absorbing material. For instance, the size cannot be larger than the size of cave and would not interfere with the cave's structure and inner components. In addition, physical differential equation of heat transfer, electromagnetic, and structural deformation have to be satisfied all the time during iteration. To sum up, the constrained functions can be described as

$$\begin{cases} \underline{x} \leq x_k^i - \frac{1}{2}x_{k+3}^i \\ x_k^i + \frac{1}{2}x_{k+3}^i \leq \bar{x} \end{cases} \quad (k = 1, 2, 3; i = 1, 2, \dots, n), \quad (6)$$

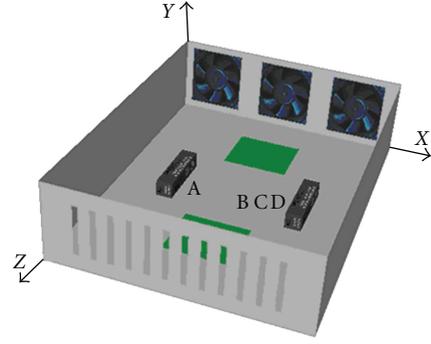


FIGURE 3: CAD model of an enclosure.

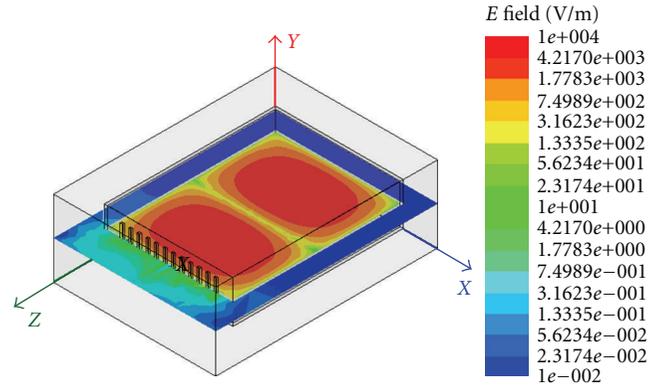


FIGURE 4: Electronic distribution without absorb.

where  $\underline{x}$  and  $\bar{x}$  are the lower and upper limit of position. Three equations are not given here.

Meanwhile, different pieces of absorbing material should not be overlapped, that means

$$\begin{aligned} (x_1^i, x_2^i, x_3^i, x_4^i, x_5^i, x_6^i) \cap (x_1^q, x_2^q, x_3^q, x_4^q, x_5^q, x_6^q) = \phi \\ (i \neq q; i, q = 1, 2, \dots, n), \end{aligned} \quad (7)$$

in which  $\phi$  is an empty set.

At the same time, the maximum temperature in equipment has to be less than and equal to the allowable value  $T_0$ , that is,

$$T_{\max} = \max\{T_i(x) \mid i = 1, 2, \dots, \text{nut}\} \leq T_0, \quad (8)$$

where nut is the total number of nodes in discrete temperature field, and  $T_i(x)$  is the temperature of the  $i$ th node.

Meanwhile, considering the cost, the sum of absorbing material should be limited

$$V(x) \leq V_0, \quad (9)$$

in which  $V(x)$  is the total volume of absorbing material and  $V(x) = \sum_{i=1}^n x_4^i x_5^i x_6^i$ .  $V_0$  is the permissible value of volume.

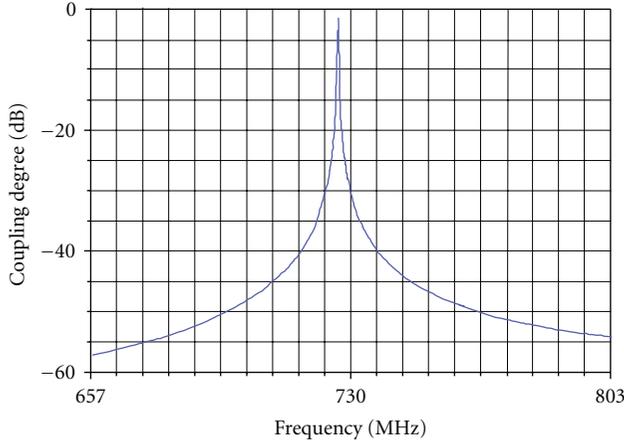


FIGURE 5: Coupling degree between two probes.

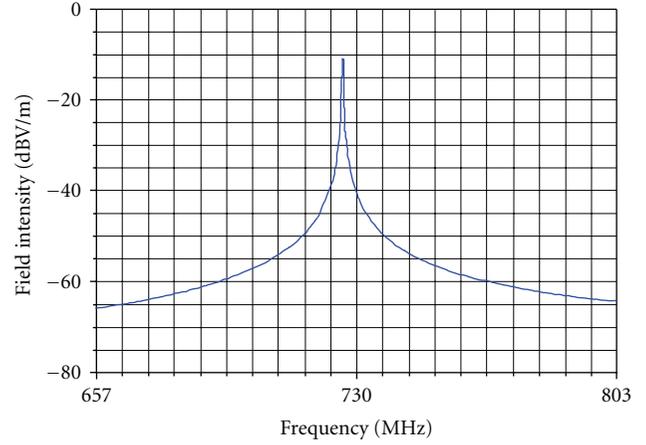


FIGURE 6: Radiation field intensity.

Up to this point, the problem can be mathematically stated as the following PI form,

$$\text{Find: } x = (x_1^1, x_2^1 \cdots x_6^1 \cdots x_j^i \cdots x_6^n)^T, \quad (10)$$

$$1 \leq i \leq n, \quad 1 \leq j \leq 6,$$

$$\text{Min: } f(x) = \alpha_1 C_{\max}(x) + \alpha_2 E_{\max}(x), \quad (11)$$

$$\text{S.T.: } \begin{cases} \underline{x} \leq x_k^i - \frac{1}{2}x_{k+3}^i \\ x_k^i + \frac{1}{2}x_{k+3}^i \leq \bar{x} \end{cases} \quad (k = 1, 2, 3; i = 1, 2, \dots, n), \quad (12)$$

$$(x_1^i, x_2^i, x_3^i, x_4^i, x_5^i, x_6^i) \cap (x_1^q, x_2^q, x_3^q, x_4^q, x_5^q, x_6^q) = \phi \quad (13)$$

$$(i \neq q; i, q = 1, 2 \cdots n),$$

$$V(x) \leq V_0, \quad (14)$$

$$T_{\max} = \max\{T_i(x) \mid i = 1, 2, \dots, \text{nut}\} \leq T_0. \quad (15)$$

Investigating the above programming problem leads us to the following points. Programming PI is a higher nonlinear programming problem, since the objective and constraint are all higher nonlinear functions of the design variable. Due to the features of electronic equipments and the optimization model, the Hooke-Jeeves method is utilized.

#### 4. Numerical Simulation, Experiment, and Discussion

To validate the above model and methodology, an enclosure (Figure 3) is investigated from both of the numerical simulation and practical experiment. They are described as follows.

**4.1. Numerical Simulation.** The size of the enclosure is  $500 \times 375 \times 125 \text{ mm}^3$ , the thickness of the wall is 2 mm, the material is aluminum. There are three fans ( $0.001 \text{ m}^3/\text{s}$  for each) in  $xoy$ -plane, evenly distributed along  $x$ -coordinate.

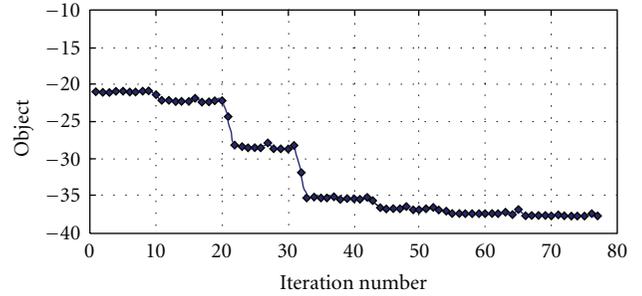


FIGURE 7: Iteration history of the objective.

On the opposite side with  $z = 500 \text{ mm}$ , twelve ventilation slots exist. Each slot is with  $100 \text{ mm}$  in length and  $10 \text{ mm}$  in width. The left and right sides of twelve slots are all  $50 \text{ mm}$ , while the top and bottom side of twelve slots are all  $12.5 \text{ mm}$ . Two heaters ( $5 \text{ W}$  for each) are fixed on the bottom (Figure 3) with  $(x, y, z) = (93.75, 0, 250)$  and  $(281.25, 0, 250) \text{ mm}$ , respectively. The size of two heaters is  $0.03 \text{ m}$ ,  $0.1 \text{ m}$  and  $0.03 \text{ m}$  in  $x$ ,  $y$  and  $z$  directions. The material is Nylon-glass filled with conduct heat coefficient  $0.214 \text{ W/m}\cdot\text{K}$ . In addition, there is an electromagnetic radiation module at position  $(x, y, z) = (187.5, 0, 125) \text{ mm}$  with the power of  $1 \text{ w}$  and a sensitive module at the position  $(x, y, z) = (187.5, 0, 375) \text{ mm}$ , both modules are treated as probes with the same size as  $5 \text{ mm}$  high in  $y$ -coordinate and all  $1 \text{ mm}$  in  $x$  and  $z$  coordinate. The focused frequency ranges from  $657 \text{ MHz}$  to  $803 \text{ MHz}$ .

The inlets, where fans located, are shielded by perforated plates whose shielding efficiency is supposed perfect due to the small pore diameter. Therefore, leakage is not considered. The leakage which should be considered is induced by the outlets that composed of twelve ventilation slots.

The discrete models  $\Gamma_1$ ,  $\Gamma_2$ , and  $\Gamma_3$  corresponding to three fields are established.  $\Gamma_1$  for structure is with  $1,374$  nodes and  $2400$  triangle elements.  $\Gamma_2$  for electromagnetic field is composed of  $1374$  nodes,  $2,400$  metallic triangles and  $10$  metallic line elements. As for temperature  $\Gamma_3$ , there are  $280,664$  elements and  $295,316$  nodes.

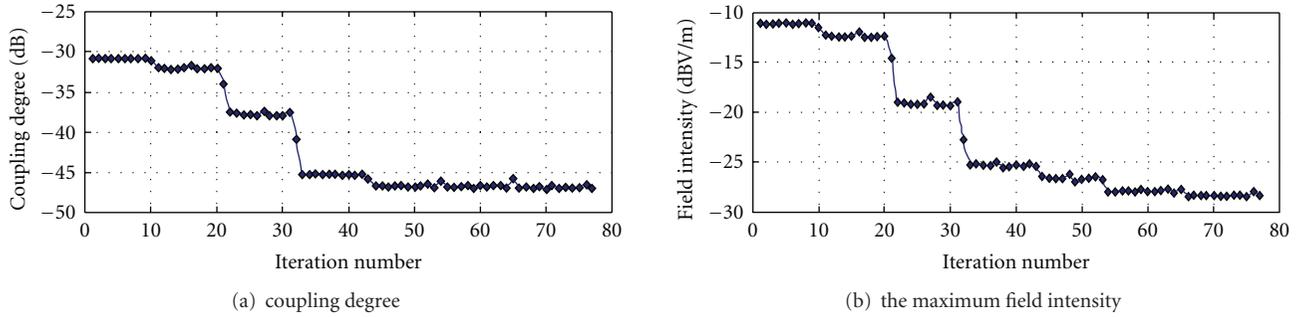


FIGURE 8: Iteration history of coupling degree and the maximum field intensity.

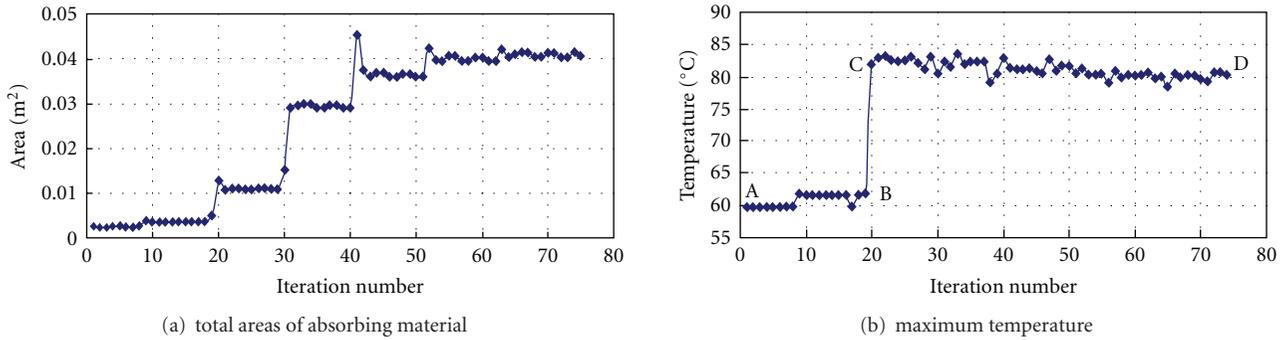


FIGURE 9: Iteration history of constraints.

Figure 4 shows that the two positions are at the top of the enclosure where the strongest electric field happened. Thus, attach two pieces of absorbing material of dielectric loss type at these points. The absorbing material is acieration foam, whose thickness is fixed as 50 mm, so two variables of thickness and center position along  $y$ -coordinate are fixed. As a result, only four independent design variables for each one are remained (Table 1). Two dimensions along  $x$ -coordinate and  $z$ -coordinate are not less than 15 mm. In Table 1,  $x_1^i$  and  $x_2^i$  ( $i = 1, 2$ ) are the center and length of the  $i$ th absorbing material along  $x$ -coordinate.  $x_3^i$  and  $x_4^i$  ( $i = 1, 2$ ) are the center and length of the  $i$ th absorbing material along  $z$ -coordinate. Resonance appears at around 730 MHz in the cave, whose mode is TE102, as showed in Figures 5 and 6. When resonance, the coupling degree related to two probes increases rapidly, as well as electromagnetic field intensity leaking from the outlets.

Suppose the admissible total volume of absorbing material is 40500 mm<sup>2</sup>, and the admissible maximum temperature is 95°C. Let  $\alpha_1 = \alpha_2 = 0.5$ . The initial values, upper and lower limits of design variables and the optimal values are given in Table 1. Figures 7–9 show the iteration history of the objective and constraint functions.

The iteration history of the objective and constraint functions are smooth, and the shielding efficiency became better with the iterations, as shown in Figure 8.

Figure 9 shows that strong relation exists between shielding efficiency and volume of absorbing material. The bigger the volume, the better the efficiency will be in suppressing the

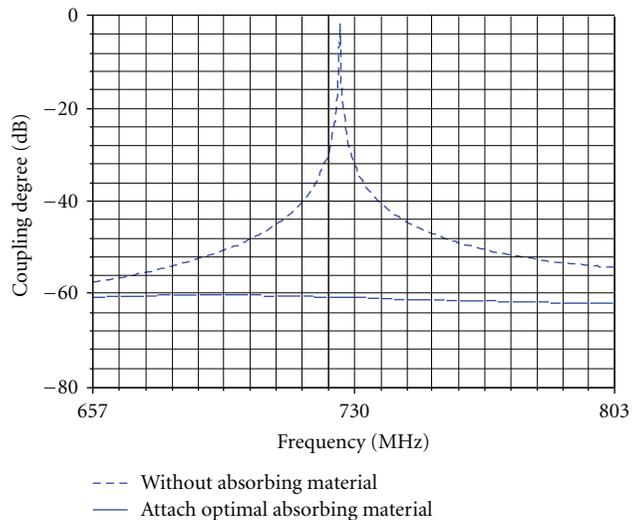


FIGURE 10: Coupling degree.

electromagnetic resonance. However, too large volume will obstruct the heat transfer. This is a conflict. Tradeoff between them is necessary.

The coupling degree between two probes and field intensity 1 meter away in the cases that there is no absorbing material or two pieces at the optimal positions, respectively, in Figures 10 and 11. It is obvious that both decreased and the efficiency is significant.

TABLE 1: Numerical optimization results.

Design variable	$x_1^1$ (mm)	$x_2^1$ (mm)	$x_3^1$ (mm)	$x_4^1$ (mm)	$x_1^2$ (mm)	$x_2^2$ (mm)	$x_3^2$ (mm)	$x_4^2$ (mm)	$C_{\max}$ (mm)	$E_{\max}$ (dBV/m)	T °C	Area m <sup>2</sup>
Initial value	180	35	117.5	35	180	35	367.5	35	-33.3	-11.6	59.69	0.0025
Optimal value	255.0	151.3	138.5	149.6	107.5	140.0	360.8	140.4	-48.7	-28.3	78.24	0.04067
Upper limit	352.5	375	242.5	250	352.5	375	492.5	250	/	/	/	/
Lower limit	7.5	15	7.5	15	7.5	15	257.5	15	/	/	/	/

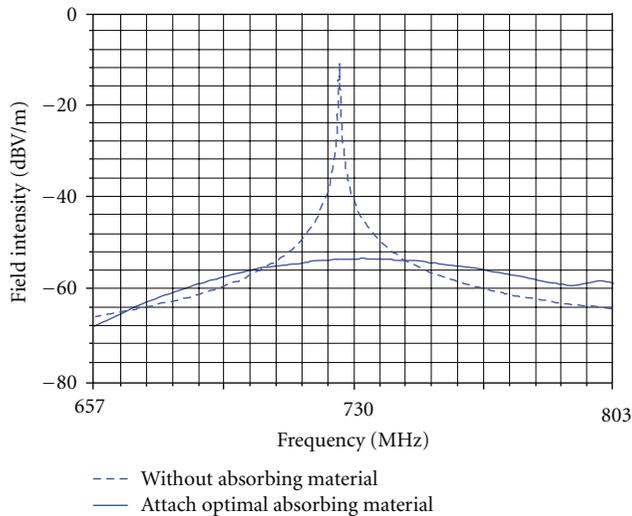


FIGURE 11: Field intensity at 1 meter away.

## 5. Concluding Remarks

The experience of theoretical analysis, numerical simulation, and practical experiment may lead us to the following conclusions.

Electromagnetic shielding of complex electronic equipment is actually a multi-field-coupling problem in theory, a new three-filed-coupling model STEM is developed in the paper.

The optimization model of searching for the best shielding performance by selecting the optimal value of the absorbing material's position and size is submitted based on the model of STEM.

The numerical experiments of equipment are carried out to demonstrate the proposed model and methodology.

It should be noted that the multi-field-coupling problem is a complex and difficult problem. The study about this is still initial, and thorough research needs to be done further.

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