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THE COUPLED PROBLEM AMONG DISPLACEMENT, THERMO AND ELECTROMAGNETIC FIELDS AND APPLICATIONS IN ELECTRONIC EQUIPMENTS

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Abstract. With the rapid development of electronic equipment, coupling problem of the displacement field, electromagnetic field and temperature field is increasingly prominent. This paper focuses on the high-density packaging system, which is a kind of typical electro-mechanical-thermal coupling equipment. To begin with, the mathematical model is established and the electrical performance is expressed as a function of structural design variables and temperature. Then, the simplification method of the electromagnetic model and the transfer technology of grid information among different physical models are discussed. Last, the mathematical model for the optimization design based on the electro-mechanical-thermal coupling model is constructed, and satisfactory results have been obtained in the application of the optimization design model to the design of a high-density cabinet.

1 INTRODUCTION

Microwave electronic equipment (reflector antenna, planar slotted antenna, active phased array radar, high-density packaging system, etc.) is widely used in various fields such as land, sea， air and space, and it is a typical combination of mechanical and electrical systems. The mechanical structure is not only the carrier and security of the electrical performance, but also restricts the improvement of the performance, showing a strong coupling characteristic between the electricity and mechanic [1]. With the development of electronic devices toward high frequency and high gain, high density and miniaturization, and fast response and high pointing precision, the performance is not only dependent on the levels of the designs of the various disciplines, but also much more on the interdisciplinary intersection and mergence, showing the multi-field coupling characteristics [2,3].

Multi-field coupling problem exists widely in the engineering practice, and has been in-depth researched in many areas and numerous valuable results have been obtained, such as the coupling contact problem researched by using the boundary element method [4,5], the coupling among different electromagnetic fields in the electronic equipment[6,7], the fluid-structure interaction problems studied with the grid matching method[8]. But for the electronic equipment, especially for the high-density packaging system, the research is still less. With the development of modern electronic devices toward miniaturization, high density, high

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frequency direction, on the one hand, the higher frequency makes electromagnetic compatibility problems of electronic devices more prominent: not only itself needs to resist against external electromagnetic environmental, but also cannot interfere the other electronic equipment nearby[9,10]. On the other hand, high density will make the cooling difficult and the high temperature would affect the performance of electronic devices. Besides, while electronic equipment is being miniaturized, the requirement of structural strength and stiffness should also be ensured and the devices must be able to work properly in the variety of conditions and harsh environment. To this end, it is necessary to in-depth research the problem from the perspective of the multi-field coupling problem and the overall system, and further to propose the field coupling theory and perform the multidisciplinary design optimization.

For the high-density packaging system, one typical kind of electro-mechanical-thermal coupling equipment, this paper establishes the multi-field coupling model and discusses the theory and method of the simplification of electromagnetic model and the transfer of grid information among different physical models. Then, based on the coupling model, the integrated optimization design model is presented. Results show that both the multi-field-coupled model and integrated optimization design proposed here are correct and valid.

2 COUPLED MODEL AMONG ELECTROMAGNETIC, TEMPERATURE, AND STRUCTURE FIELDS

For the high-density packaging cabinet, the electromagnetic (EM) shielding effectiveness is one key performance. Assume that there are M electronic devices in its box and e_i is the electric field intensity generated by the ith device. P is of the distance of d from the center of the box. Let the field intensity amplitude at P be $\left|\sum_{i=1}^{M} E_i(e_i)\right|$ with box and $\left|\sum_{i=1}^{M} E_i^0(e_i)\right|$ without box. Then the EM shielding effectiveness (SE) is

$$\mathrm{SE} = 20log\left(\left|\sum_{i=1}^{M} E_i^{0}(e_i)\right| \Big/ \left|\sum_{i=1}^{M} E_i\left(e_i\right)\right|\right) \tag{1}$$

In engineering practice, there are a lot of factors that affect SE. Assume that the cabinet has n leak paths and SE_i is the shielding effectiveness of the ith leak, then the SE considering all the factors is[1, 11]

$$\mathrm{SE}_{dB} = -20log\left(\sum\nolimits_{i=1}^{n} 10^{-\mathrm{SE}_i/20}\right) \tag{2}$$

The physical meaning of formula (2) is that SE of the cabinet is mainly determined by the leakage factor with the lowest SE. But there are several shortages. Firstly, when considering only one single factor, the analytical precision is limited and the influencing factors not able to be expressed by a formula, say, the gap closed by conductive rubber, is difficult to be considered. The second shortage is that the coupling characteristic of the electromagnetic field, structural displacement and temperature of electronic equipment is ignored, for example, the cabinet would be deformed under loads and the characteristic of electromagnetic radiation would be changed under different temperature. Next, the model of high-density packaging cabinet will be derived from the angle of the multi-field coupling analysis.

2.1 The influence of structural parameters and deformation

Various holes and seams on the cabinet's surface are partial main factors that affect SE. Structural parameter $\boldsymbol{\beta}$ involves the wall thickness, stiffeners, the size and position of internal partitions, vents and seams, the position of the internal electromagnetic devices, and so on. The external electric field is a function of $\boldsymbol{\beta}$. Under the external loads, the cabinet is deformed resulting in the change of the induced current on the surface acting as the electromagnetic boundary and then SE will be to some extent affected. Although the effect is small, it is still well worth being researched in theoretical study. In addition, structural deformation will also lead to the position change of the internal devices and then affect the leakage of electric field. Considering structural deformation δ is the function of $\boldsymbol{\beta}$, the leakage electric field can be written as

$$\sum_{i=1}^{M} E_i\left(e_i, \delta(\boldsymbol{\beta})\right) \tag{3}$$

And the SE can be described as

$$\mathrm{SE} = 20log(\left|\sum_{i=1}^{M} E_i^{0}(e_i)\right| \Big/ \left|\sum_{i=1}^{M} E_i\left(e_i, \delta(\boldsymbol{\beta})\right)\right|) \tag{4}$$

2.2 The influence of temperature

While the cabinet working, the internal devices generate heat and their performance will be affected by the changing temperature to a certain extent. So the electric field strength generated by the electromagnetic devices can be considered to be a function of the temperature *T*. Generally, the influence relationship will be described by a curve or chart that can be used by looking up in according to the temperature. Besides, the influence of temperature on the structural deformation can be written as $\delta(\boldsymbol{\beta}, T)$, so the leakage electric field can also be expressed as

$$\sum_{i=1}^{M} E_i\left(e_i\left(T\right), \delta(\boldsymbol{\beta}, T)\right) \tag{5}$$

Then SE is

$$\mathrm{SE} = 20log(\left|\sum_{i=1}^{M} E_i^{0}(e_i)\right| \Big/ \left|\sum_{i=1}^{M} E_i\left(e_i(T), \delta(\boldsymbol{\beta}, T)\right)\right|) \tag{6}$$

2.3 The influence of contact gap

In the cabinet with high SE, the contact gap is generally closed by such materials as conductive gasket to ensure electrical continuity of the contact surface in order to reduce the leakage. For the gaps closed by conductive gaskets, it can be assumed that they can be replaced by some equivalent conductive materials with the same leakage electric fields. According to the transfer impedance of the contact gap or conductive rubber obtained by testing and their structural parameters, the electromagnetic parameters, such as conductivity, can be derived. By now, the geometric model of the cabinet can be established in the simulation software and then the field distribution near the cabinet can also be calculated after the material parameters and excitation source being set.

Here suppose that W_1 and W_2 represent the height of the gap and filling material respectively. The transfer impedance is Z and the area of the gap is S = length × width. Then the conductivity (σ_T) of filling material is

$$\sigma_T = \sqrt{W_1 W_2} \big/ SZ \tag{7}$$

Then the leakage electric field can be calculated with the material parameters above. For the conductive rubber, the compressed height h can also be used directly, the conductivity is

$$\sigma_T = h \big/ SZ \tag{8}$$

The leakage electric field of the cabinet with contact gaps is the function of transfer impedance Z and simultaneously Z is closely related to the frequency *freq*, so the leakage electric field can be expressed as

$$\sum_{i=1}^{M} E_i\left(e_i(T), \delta(\boldsymbol{\beta}, T), Z\left(freq\right)\right) \tag{9}$$

Eventually, SE can be further rewritten as [12, 13],

$$\mathrm{SE} = 20log(\left|\sum_{i=1}^{M} E_i^{0}(e_i)\right| \Big/ \left|\sum_{i=1}^{M} E_i\left(e_i(T), Z(freq), \delta(\boldsymbol{\beta}, T)\right)\right|) \tag{10}$$

The above formula is just the electro-mechanical-thermal coupling model of the high-density packaging cabinet. It reflects the interrelationship among structure field, electromagnetic field and temperature field, and the electrical performance is expressed as a function of structural design variables (e.g., structural size, shape, topology, and type), which makes it possible to perform the electro-mechanical-thermal integrated optimization design.

3 SOLUTION OF MULTI-FIELD COUPLING MODEL

Sequential coupling analysis method is an iterative method solving each field in turn within a time step and transferring coupling information among different fields, and it is applicable to low non-linear coupling problems [14, 15]. Because of its advantage of separately modeling, easily using respective simulation tools, software reuse and modularizing, the method is widely used in solving coupling problems. Of course, this method is used to solve the multi-field coupling model in this paper.

3.1 Simplification of electromagnetic model

Electromagnetic simulation needs to create a geometric model of the electronic equipment. However the actual model is very complicated with a lot of fine structures, such as various bosses, grooves, counterbores, and so on. If the simulation model is established in accordance with the actual model, it will not only dramatically increase the computational workload, but also it is not necessary in engineering. For this reason, this paper presents a method for the simplification of the tiny structures based on perturbation theory.

Generally, the SE would be worst at the resonant frequency. So the simplified model should be able to reflect the actual resonant frequency and ensure its offset within the permissible error range. Because simplification mainly affects the offset of the resonant frequency, if let the offset $|\Delta\omega/\omega_0| < \varepsilon$, the volume ΔV of the fine structure can be ignored only when $\Delta V < \varepsilon V_0 / f(x, y)$. Where, $f(x, y)$ is a proportionality constant related to the position of the perturbation and the resonance mode excited in the cavity and would act as a dominant role when the rectangular cabinet works at the frequency lower than 1GHz. Engineering experience shows that the general range for the threshold ε is $0 < \varepsilon < 0.01$. Let ε =0.01, it means that the change of the resonant frequency after the perturbation is less than 1% of the original resonant frequency. Now the volume of the tiny structure that can be ignored is $\Delta V \le \varepsilon V_0 / f(x, y)$, where, V_o is the original chamber volume.

3.2 Transfer of grid information

The transfer of grid information among different physical fields is a key problem in the coupling analysis. Generally, because of the different forms and precision of grids of different fields, the grid mismatch at the common interface of the different physical fields occurs and grid overlap and gap will also occur at the same time [2]. Fig.1 shows the mismatch in a two-dimensional case, where, Γ is the common smooth interface, Γ_A and Γ_B the discrete boundaries of different fields. In the coupling analysis, the information transfer relationship of Γ_A and Γ_B must be established through the method of mathematical physics.

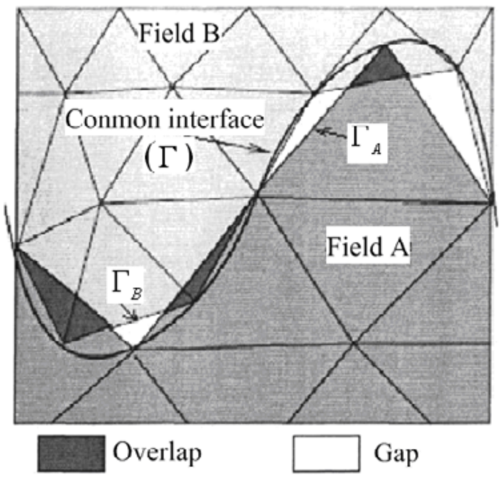

Figure 1: Schematic diagram of the grid dismatch

Electronic equipment usually involves the displacement field, electromagnetic field and temperature field, it's necessary to transfer coupling information among physical fields. The most common way is to transfer the structure deformation to the electromagnetic analysis module and temperature analysis module, and then to carry out the calculation of temperature and electromagnetic field. In this paper, PRO/E is used for parametric modeling, ANSYS for structural analysis, FEKO for electromagnetic analysis and ICEPAK for temperature analysis.

In the structural finite element analysis, shell element mainly includes triangular element and quadrilateral element, and solid element involves tetrahedral cell and hexahedron element. It is known that the software ICEPAK used for temperature calculation can recognize the model assembled by triangular planes, the node coordinates and cell information of the outer surface of the deformed structure grid can be used to produce triangular planes and then generate the corresponding grid files that can be identified by FEKO and ICEPAK software respectively, ultimately achieving the transfer of grid information [13], as shown in Fig.2.

To begin with, based on the grid files proposed above, the thermal analysis model and electromagnetic analysis model can be produced. Then, temperature analysis will be performed. According to the temperature analysis results, the powers of the electromagnetic devices in the model can be determined, and the electric parameters of contact gap or conductive rubber are calculated at the same time. Lastly, the electromagnetic analysis can be able to be carried out with the electromagnetic analysis model, and thus the multi-field coupling analysis is realized.

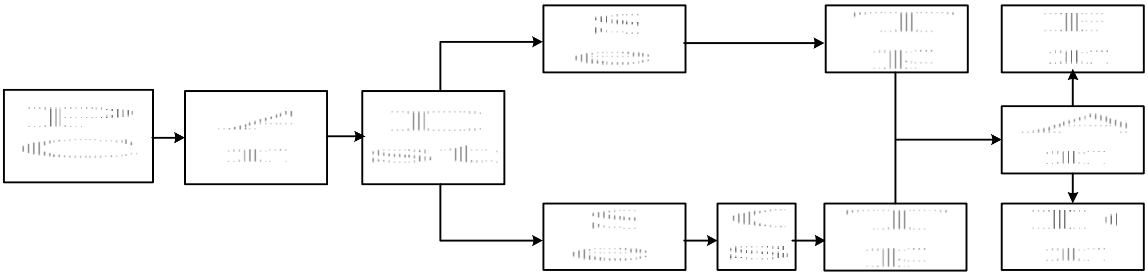

Figure 2: Procedure diagram of the transfer of deformation information

4 MATHEMATICAL DESCRIPTION OF INTEGRATED OPTIMIZATION DESIGN

Structural strength, ventilation and cooling, and electromagnetic compatibility are the three main aspects in the design of high-density packaging cabinets, and there are contradictions among each other. The first contradiction exists between the mass and strength. The requirement for structural strength is very strict to ensure that it can work properly under various conditions of shock and vibration, but the working environment requires small size and light weight, especially for the airborne and missile-borne equipment. For another kind of electric equipment such as radar and antenna, the contradiction between the mass and stiffness is the major one. Second one exists between the ventilation and electromagnetic shielding effectiveness. Larger hole or seam is conducive to cooling but not to SE, and high temperature would affect the performance of electronic devices. In order to meet all the requirements at same time, it is necessary to in-depth research the problem from the angle of the multi-field coupling problem and the overall system, and to perform the multidisciplinary integrated optimization design.

The establishment and solution of the multi-field coupling model make the integrated optimization design possible, thus the requirements can be met simultaneously for structural stiffness and strength, ventilation and cooling, and electromagnetic compatibility. Based on formula (10), the mathematical description of the electro-mechanical-thermal coupling optimization model of high-density packaging system can be expressed as follows [12,13,16],

$$\begin{aligned} & find \ \boldsymbol{\beta}=(\beta_1,\beta_2,\cdots,\beta_{N_d})^T \\ & \min \ \mathrm{W}(\boldsymbol{\beta}) \\ & s.t. \ \ \text{-SE}(\boldsymbol{\beta})+SE^0 \le 0 \\ & \qquad -f_{eigen}+f_{eigen}^0 \le 0 \\ & \qquad T_{j\max}(\boldsymbol{\beta})-T_{j\max}^0 \le 0, \ j=1,2,\cdots,N_u \\ & \qquad \sigma_i-[\sigma] \le 0, \ i=1,2,\cdots,N_m \\ & \qquad \beta_{k\min} \le \beta_k \le \beta_{k\max}, \ k=1,2,\cdots,N_d \end{aligned} \tag{11}$$

Where, $\mathrm{W}(\boldsymbol{\beta})$ is the structural weight, $\mathrm{SE}(\boldsymbol{\beta})$ and SE^0 the actual value and minimum allowable value of SE, f_{eigen} and f_{eigen}^0 the actual value and minimum allowable value of natural frequency, $T_{j\max}(\boldsymbol{\beta})$ and $T_{j\max}^0$ the actual value and maximum allowable value of the temperature at the *j*th point, $\beta_{k\max}$ and $\beta_{k\min}$ the upper and lower limits of variable β_k, N_d, N_u and N_m the total numbers of the design variables, temperature constraints and stress constraints respectively.

Here the weight is used as the objective function, besides, SE or both can also be used as the objective function according to the actual situation. Investigating the above programming problem leads us to the following points. The coupling optimization model is a highly nonlinear programming problem, since the objecive and constraints are all highly nonlinear functions of the design variables. So the optimization algorithm and efficiency are two main topics needed to be further researched.

5 ENGINEERING APPLICATION AND DISCUSSION

In this section, the optimization design of an airborne electronic equipment cabinet is performed with the multi-field coupling optimization model [13,17]. The box structure is shown in Fig.3. The length, width and height of the aluminum box are 575mm, 482mm, and 532mm respectively. The box is divided into two parts inside: the upper part is installed with 12 PCB planes and two powers, while the lower part is ventilation duct with an inclined wind shield. The upper part of the box front panel has two groups of radiating holes and its lower part has two fans. Besides, three fans are installed in the upper part of the back panel. The box is installed in plane, so there is a requirement for the fundamental frequency and weight. Thus, the goal of this paper is to reduce the weight, and the highest temperature inside the cabinet, SE, the first natural frequency and maximum stress all act as constrains, the size and position of the holes, the wall thickness of the cabinet, and wind shield length are design variables.

There are 8 design variables which can be divided into three kinds. The first category is the position and size of the holes, including the aperture length L and width W, distance d1 from hole to left side plate, distance d2 from hole to the power supply, distance d3 between holes and distance d4 between hole columns. The second category is the wall thickness D1 and the third is the length D2 of the wind deflector. Thus design variables can be expressed as follows,

$$\boldsymbol{\beta}=(\mathrm{L},\mathrm{W},\mathrm{d1},\mathrm{d2},\mathrm{d3},\mathrm{d4},\mathrm{D1},\mathrm{D2})^T \tag{12}$$

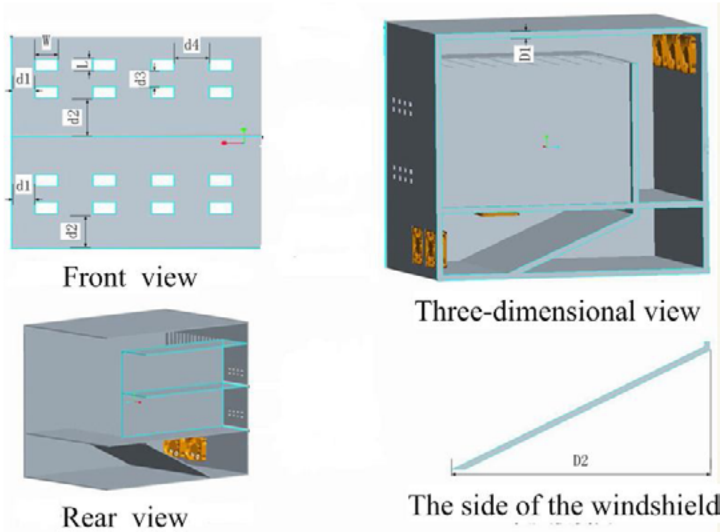

Figure 3: Schematic diagram of an airborne cabinet

Table 1: Coupling optimization results

Item	Name	Initial Value	Optimal Value	Lower Limit	Upper Limit
Variable	D1	4.5mm	3.75mm	2mm	6mm
	D2	300mm	50mm	50mm	400mm
	L	10mm	20mm	5mm	30mm
	W	10mm	5mm	5mm	50mm
	d1	20mm	50mm	5mm	80mm
	d2	20mm	20mm	5mm	80mm
	d3	15mm	15mm	5mm	50mm
	d4	15mm	15mm	5mm	30mm
Object	Weight	72.25/Kg	67.71/Kg	/	/
Constraint	Max stress	81.9/MPa	118/MPa		150/MPa
	Natural frequency	73.80/Hz	73.69/Hz	70/Hz	
	SE	28.80/dB	42.07/dB	35/dB	
	Temperature of power1	71.9/℃	65.33/℃		75/℃
	Temperature of power2	73.98/℃	70.52/℃		75/℃

The optimization goal is to reduce the weight W,

$$min \quad W(\boldsymbol{\beta}) \tag{13}$$

The external load on the center position of the upper cover board is a downward force of 100N, and the first natural frequency and maximum stress act as structural constraints,

$$-f+[f_e]\leq 0 \tag{14}$$

$$\sigma_{max}-[\sigma_e]\leq 0 \tag{15}$$

The constraint for the temperature is the maximum temperature inside the cabinet. Through preliminary analysis, the maximum temperature occurs at the power supply, so the temperatures of the two power supplies both act as constraints. Here it is noted that the power dissipation is 160W for two supplies,

$$T_{i\max}\leq T_e \quad (i=1,2) \tag{16}$$

The frequency here is 300MHz and SE acts as a constraint,

$$-\mathrm{SE}(\boldsymbol{\beta})\leq -SE^e \tag{17}$$

In the above formulas, f_e , σ_e , T_e and SE^e are the allowable minimum natural frequency, maximum stress, maximum temperature and nimum SE respectively. According to the features of the electronic equipment and the optimization model, the Hooke-Jeeves method is utilized here, and the optimizing results are denoted in Table 1.

The table 1 shows that the optimized weight decreases by 6.3% mainly because the wall becomes thinner and the wind shield becomes shorter, and the maximum stress increases but is still within the constraint. At the same time, the first-order natural frequency is hardly influenced. The radiating holes change from cube to rectangle making the electromagnetic leakage less, thus increasing the EM shielding effectiveness. Last the highest temperature is lowered. Clearly, only through once optimization, the overall performance is improved obviously.

6 CONCLUSION

Electronic equipment is a multi-disciplinary system, and the electromagnetic shielding of complex electronic equipment is actually a multi-field coupling problem in theory.

Firstly, starting from the angle of the multi-field coupling problem and interdisciplinary intersection and mergence, the multi-field coupling model of the high-density packaging system have been estblished. Then, the theory and method of the simplification of complex electromagnetic model based on perturbation theory and the transfer of grid information are discussed. Lastly, the multi-field coupling optimization model is presented and applied to the design of a high-density cabinet, showing that through the multidisciplinary optimization design, the overall performance of the electronic equipment is improved obviously.

However, it should be noted that multi-field coupling problem is a complex and very difficulty issue. Many problems, such as modeling of circuit boards, thermoelectric strong coupling problem, optimization algorithms and efficiency, and application of surrogate models, need to be researched in depth. Besides, the research and application of multidisciplinary optimization methods should be strengthened in the future study.

In breif, deep research in the electromechanical coupling theory and method is of great significance to the design of high-performance electronic equipment, and thorough research needs to be done further.

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