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특수경계요소와 유한요소·경계요소병용법을 이용한 2단계 최적설계법

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A Novel Design Approach Composed of Two Sequential Processes Using the Specific BE and Hybrid FE-BE Method

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Abstract - This paper presents a novel design approach composed of two sequential processes for 3D magnetic shielding problems, which results in the global optimum solution in a shorter time. The feature of the proposed approach is the adoption of the specific boundary element with permeability of infinity. Assuming the permeability of infinity enables us to regard the thickness of ferromagnetic shields as infinitesimal, and thus to simplify the investigated model adequately in numerical analysis. This reduces the number of unknown variables and saves us a large amount of CPU-time for grasping the broad characteristics of the model. Some numerical results that demonstrate the validity of the proposed approach are also presented.

1. INTRODUCTION

Recently, in designing electromagnetic devices, the application of optimization methods coupled with magnetic field analysis is receiving ever-increasing attention, and a large number and variety of methods have been proposed [1]. For instance, the shielding problem has been of great interest in the area of medical service adopting the superconducting magnets. The conventional optimization method, however, has some difficulties in practical use because of many iterations and time-consuming, especially for 3D problems.

With this background, this paper presents a novel design approach for 3D magnetic shielding problems, which results in both an overall increase in optimization speed and the global optimum solution. Here, we investigate the magnetostatic shielding problem, which is typical of the model whose most part consists of the air region. The model of this kind is usually free from intense magnetic saturation, and magnetic reluctance of the shields, i.e. the permeability of the magnetic materials, does not influence the results seriously. Thus, we propose the adoption of the specific boundary element (BE) with permeability of infinity. Assuming the permeability of infinity enables us to regard the thickness of shields as infinitesimal and to simplify the investigated model adequately in numerical analysis. This reduces the number of unknown variables as well as that of boundary elements, and saves us a large amount of CPU-time.

The feature of this study is to divide the optimization procedure into two processes. In the first process, using the above-mentioned simplified model in numerical implementation, we perform the optimization procedure over a wide variety of design variables in the vast domain to grasp the broad characteristics of the problem. Then, we decide the adequate design variables preventing the local optimum solution. In the second process, regarding the configuration obtained in the first process as the initial one, we accomplish the design optimization in more detail by the ordinary numerical analysis of magnetic fields; the hybrid finite element and boundary element (FE-BE) method is implemented in this paper [2][3]. As regards the search algorithm, the genetic algorithm (GA) is adopted through both the first and second processes. The GA is a powerful search method based on probabilistic evolution through generations, which consists of three fundamental operators upon the string structures, i.e. reproduction, crossover, and mutation [4][5].

Finally, the validity of the proposed approach is examined by comparing the magnetic flux distributions between the initial and optimized configurations of the concrete model, i.e. the MRI magnet system with magnetic shielding. In this example the whole CPU-time to obtain a satisfactory solution is much shortened compared with the case of the conventional approach.

2. SPECIFIC BOUNDARY ELEMENT

Here, we adopt the boundary element using the magnetic scalar potential Ψ as the physical quantity. The boundary integral equation is given as follow:

$$C_P\ \Psi_P = \int_\Gamma \frac{\partial\ \Psi_Q}{\partial n}\frac{1}{r}\,d\Gamma - \int_\Gamma \Psi_Q \frac{\partial}{\partial n}\left(\frac{1}{r}\right)d\Gamma + \int_\Omega \nabla\frac{1}{r}\cdot dm \qquad (1)$$

where m is the magnetic dipole moment due to exciting currents[6]. Introducing the specific BE with permeability of infinity into (1), we can regard the thickness of shields infinitesimal approximately in numerical analysis and can reduce the number of boundary elements to less than half as shown in Fig. 1. On the boundaries Γ_α and Γ_β which overlap each other, the following conditions are obtained as

$$\Psi_{\Gamma_\alpha} = \Psi_{\Gamma_\beta} \quad \text{constant on } \Gamma \qquad (2)$$

$$\int_{\Gamma_\alpha}\frac{1}{r}\,d\Gamma = \int_{\Gamma_\beta}\frac{1}{r}\,d\Gamma \qquad (3)$$

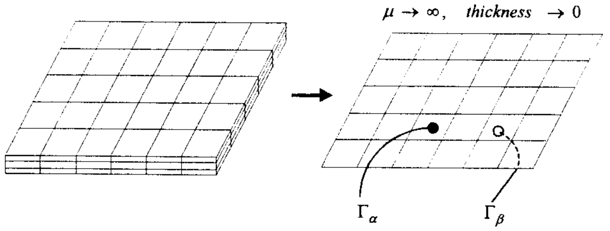

Fig. 1. Specific Boundary Elements

$$\int_{\Gamma_\alpha} \frac{\partial}{\partial n}\left(\frac{1}{r}\right) d\Gamma = -\int_{\Gamma_\beta} \frac{\partial}{\partial n}\left(\frac{1}{r}\right) d\Gamma \qquad (4)$$

By using these conditions, we can decrease the number of unknown variables and can rewrite (1) in reduced form as

$$C_P \Psi_P = \int_\Gamma q \frac{1}{r}\, d\Gamma + \int_\Omega \nabla \frac{1}{r} \cdot dm \qquad (5)$$

where

$$q = \frac{\partial \Psi_{\Gamma_\alpha}}{\partial n} - \frac{\partial \Psi_{\Gamma_\beta}}{\partial n} \qquad (6)$$

Further, since $\nabla \cdot B = 0$, we have

$$\int_\Gamma q\, d\Gamma = 0 \qquad (7)$$

Coupling (5) and (7), we can obtain the unknown variables Ψ and q on the boundaries. Finally we estimate the magnetic flux density B in the air region by calculating the negative gradient of (5) analytically.

3. NUMERICAL EXAMPLE

3.1 Investigated Model

The MRI magnet system with a ferromagnetic shield is designed as an application example of the proposed approach. The investigated model is symmetric with respect to the $z=0$ plan and axisymmetric to the z-axis. The cross-section of the quadrant of this model with six design variables is shown in Fig. 2, where d_i $(i=1,2,3)$ are the lengths of coils, d_i $(i=4,5)$ are the distances between coils, and J_1 is the source current density. The thickness and radiuses of coils and the shape of the ferromagnetic plate are fixed. The ferromagnetic plate is treated as magnetic material with the relative permeability of 1000. The goal of the optimization is to make the magnetic flux distribution in the observation area homogeneous and to determine the appropriate position and size of each coil, and their current density. The magnetic field homogeneity η, i.e. the object function, is defined as

$$\eta = \frac{B_{max} - B_{min}}{B_0} \qquad (8)$$

where B_{max} and B_{min} are the maximum and minimum values of the magnetic field densities in the observation area, and B_0 is the flux at the center of the magnetic system, which is constrained to be of 1.5 T.

3.2 Simplification of the Model

Here, we apply the previously stated specific BE with the permeability of infinity to the investigated model. Introducing the specific BE technique enables us to regard the thickness of shield as infinitesimal in numerical analysis. To simplify the model further, we adequately substitute the line currents for the volume currents of coils as shown in Fig. 3. The influence of these currents is evaluated by using the analytical integration containing only the elementary functions [6]. Compared with the analysis of the actual model by the hybrid FE-BE method, the CPU-time is much shorten to about 1%. The discretization data in this example are shown in Table 1.

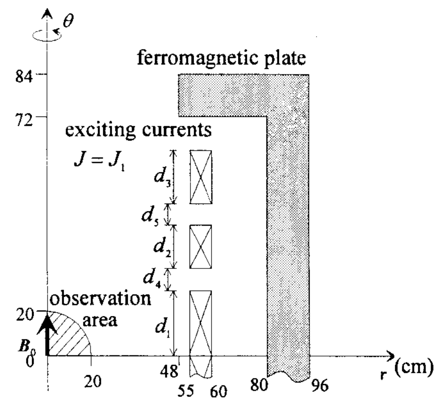

Fig. 2. Investigated Model

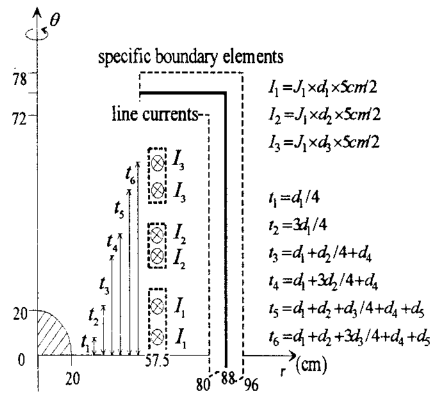

Fig. 3. Simplified Model

Table 1. Discretization Data

Item	Specific BE Method (Simplified Model)	Hybrid FE-BE Method (Actual Model)
Nodes	60	378
Boundary Element	59	138
Finite Element	-	620
Unknown Variables	60	516

3.3 Optimization Procedure and Results

Unlike the conventional approach consisting of one optimization process, the proposed optimization procedure is composed of two sequential processes.

In the first process, using the above-mentioned simplified model in numerical implementation, we grasp the broad characteristics of the problem as a preliminary analysis and reduce the domain of the design variables adequately. Varying only one of the design variables with the other ones fixed, we calculate the field homogeneity η of the observation area (see Fig. 4). The homogeneity η decreases with increasing length d_i $(i=1,2,3)$. Considering the tendencies indicated in Fig. 4 we decide the domain of the design variables as in Table 2, and carry out the optimization procedure by the GA combined with the specific BE. The initial population of the search has 100 members. The members of the initial population are created by randomly placing the binary code of {0,1} into the bit positions of the chromosomes. Each of the six design variables is coded into a 9-bit string segment using binary coding as shown in Table 2. Both the roulette wheel and elite technique are implemented, for the reproduction operator, and the one-point crossover rule for the crossover operator. The occurrence probability is of 0.05 for mutation. The decision on the convergence of solutions is made based on the fitness, i.e. the objective function values, of the population. The optimization results in this process are shown in Table 2.

In the second process, regarding the configuration obtained in the first process as the initial one, we accomplish the design optimization in more detail by the GA combined with the hybrid FE-BE method. Here, based on the optimization results obtained as in Table 2, the domain of the design variables is furthermore reduced from 54 bits to 42 bits, i.e. $1/2^{12}$, as in Table 3.

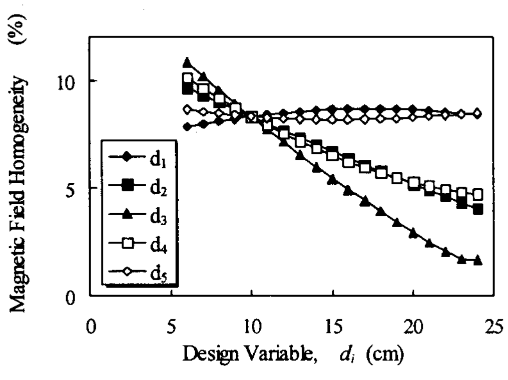

Fig. 4. Variation of Magnetic Field

Table 2. Results of First Process

Design Variables	Domain	Optimization Results
d_1 (cm)	3~11 → 9 bits	4.36
d_2 (cm)	14~22 → 9 bits	21.16
d_3 (cm)	14~22 → 9 bits	21.10
d_4 (cm)	12~20 → 9 bits	13.44
d_5 (cm)	4~12 → 9 bits	5.52
$J_1\times10^7$ (A/m^2)	2~10 → 9 bits	4.10
String Structure	54-bit length	-

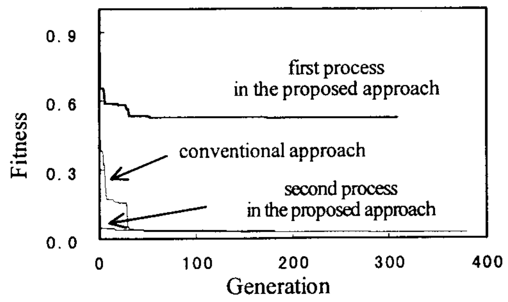

Fig. 5. Variation of Fitness

Table 3. Results of Second Process and Conventional Approach

Design Variables	Second Process		Results of Conventional Approach
	Domain	Optimization Results	
d_1 (cm)	3.5~5.5 → 7 bits	5.44	6.26
d_2 (cm)	20~22 → 7 bits	22.38	21.12
d_3 (cm)	20~22 → 7 bits	21.62	18.90
d_4 (cm)	12~14 → 7 bits	12.26	13.70
d_5 (cm)	4.5~6.5 → 7 bits	6.66	11.62
$J_1\times10^7$ (A/m^2)	3~5 → 7 bits	3.84	3.12
String Structure	42-bit length	-	-

Table 4. Homogeneity and Iteration

	Proposed Approach		Conventional Approach
	First Process	Second Process	
Homogeneity	14.6005	0.8268	0.8174
Iteration	30800	9100	38200

The final optimization results are also shown in Table 3, and are compared with those of a conventional approach (see Tables 3 and 4). The results obtained by both these approaches are approximately in agreement with each other. On the other hand, Fig. 5 shows the change of the average fitness over generations; the average fitness converges remarkably rapidly in the second process of the proposed approach, which verifies the first process is very effective as a preliminary analysis. There is little time-consuming in the first process owing to the specific BE technique. Consequently, in this example, the whole CPU-time to obtain a satisfactory solution is much shortened to about 25% compared with the case of the conventional approach.

4. CONCLUSION

A novel design approach composed of two sequential processes for 3D magnetic shielding problems is presented. The proposed approach, in which the specific BE with permeability of infinity is adopted, results in the global optimum solution in a shorter time. Some numerical results that demonstrate the validity of the proposed approach are also presented.

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