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Magnetic Shield Design of Perpendicular Magnetic Recording Head by Using Topology Optimization Technique

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It is necessary to develop a recording head having large recording field and small stray field to adjacent tracks and adjacent bits in perpendicular magnetic recording system. In this paper, in order to decrease the leakage flux in the adjacent bit, the approach of magnetic shield design of perpendicular magnetic recording head for 200 Gb/in^2 is performed by using the topology optimization technique.

***Index Terms*—Perpendicular magnetic recording head, sensitivity analysis, shield design, topology optimization.**

I. Introduction

The perpendicular magnetic recording system is considered as an important technique for the high density magnetic recording exceeding 100 Gb/in^2 [1]. On the other hand, when the linear recording density (BPI) is increased, the erase of bits due to the stray field becomes remarkable. In order to decrease the leakage flux to adjacent bits, it is considered to set the magnetic shield along the down-track direction. The optimization technique utilizing the finite-element method (FEM) is effective to get an optimal magnetic shield. Recently, the topology optimization technique [2] has been investigated to design the magnetic circuit of new concept.

In the topology optimization by using the density method [3], [4] combined with a descent method, the relationship between the material constant and the material density is continuous, then, there occurs a grayscale element. It is not clear whether this region can be treated as magnetic material or not [5]. Therefore, the topology optimization method using the genetic algorithm is presented [6]. This method is superior to the density method from the viewpoint that no grayscale element appears and the calculation of sensitivity is not required. However, a continuous shape cannot be often obtained, because the magnetic material is distributed discretely due to huge design variables. More investigation is desired for the practical utilization of this method.

In this paper, a topology optimization algorithm (ON/OFF method [7]) considering the existence of material (ON/OFF) in each element is adopted. In order to prevent the discretized topology, the existence of magnetic material in each element is decided by using the sensitivity. As the fast calculation of sensitivity is desired in order to decrease the total CPU time, the adjoint variable method [8], [9], in which only one extra calculation is required, is applied. Moreover, to decrease the number of Newton–Raphson iteration in the nonlinear analysis, the line search method [10] is introduced. As a result, an effective write head and magnetic shield is designed quickly by using the ON/OFF method.

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II. Topology Optimization Technique

A. Sensitivity Analysis Method

The sensitivity is accurately calculated by using the adjoint variable method [8], [9]. The equation for FEM is given as

$$\boldsymbol{H}A = \boldsymbol{G} \tag{1}$$

where $\boldsymbol{H}$ is the coefficient matrix, $\boldsymbol{A}$ is the column vector of magnetic vector potential, and $\boldsymbol{G}$ is the right-hand side vector. Taking the derivative of (1) with design variable p_k in an element k

$$\frac{\partial \boldsymbol{H}}{\partial p_k}\boldsymbol{A} + \boldsymbol{H}\frac{\partial \boldsymbol{A}}{\partial p_k} = \frac{\partial \boldsymbol{G}}{\partial p_k} \tag{2}$$

(2) can be rewritten as follows:

$$\frac{\partial \boldsymbol{A}}{\partial p_k} = \boldsymbol{H}^{-1}\left(\frac{\partial \boldsymbol{G}}{\partial p_k} - \frac{\partial \boldsymbol{H}}{\partial p_k}\tilde{\boldsymbol{A}}\right) \tag{3}$$

where $\tilde{\boldsymbol{A}}$ is the value obtained by solving (1). If the objective function is expressed as the function $W(p_k, \boldsymbol{A})$ of the permeability in design domain and the magnetic vector potential, the sensitivity is given by

$$\frac{\mathrm{d}W}{\mathrm{d}p_k} = \frac{\partial W}{\partial p_k} + \frac{\partial W^T}{\partial \boldsymbol{A}}\frac{\partial \boldsymbol{A}}{\partial p_k}. \tag{4}$$

Substituting (3) into (4), (5) can be obtained:

$$\frac{\mathrm{d}W}{\mathrm{d}p_k} = \frac{\partial W}{\partial p_k} + \frac{\partial W}{\partial \boldsymbol{A}}^T \boldsymbol{H}^{-1}\left(\frac{\partial \boldsymbol{G}}{\partial p_k} - \frac{\partial \boldsymbol{H}}{\partial p_k}\tilde{\boldsymbol{A}}\right). \tag{5}$$

In order to avoid the calculation of the inverse of $\boldsymbol{H}$, an adjoint vector λ is introduced [8]. The adjoint equation is given by

$$\boldsymbol{H}^T\boldsymbol{\lambda} = \frac{\partial W}{\partial \boldsymbol{A}} \tag{6}$$

λ is obtained by solving (6), and $\mathrm{d}W/\mathrm{d}p_k$ is calculated by substituting λ into (7)

$$\frac{\mathrm{d}W}{\mathrm{d}p_k} = \frac{\partial W}{\partial p_k} + \boldsymbol{\lambda}^T\left(\frac{\partial \boldsymbol{G}}{\partial p_k} - \frac{\partial \boldsymbol{H}}{\partial p_k}\tilde{\boldsymbol{A}}\right). \tag{7}$$

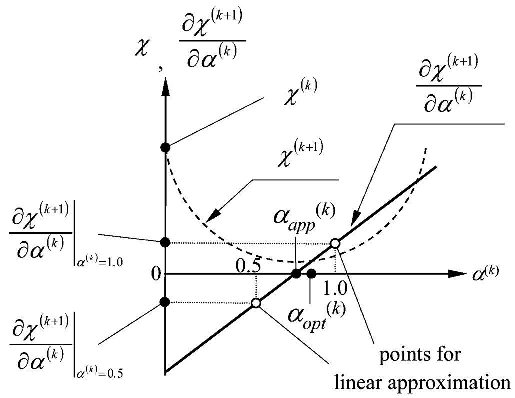

Fig. 1. Method for determining step size by using linear approximation.

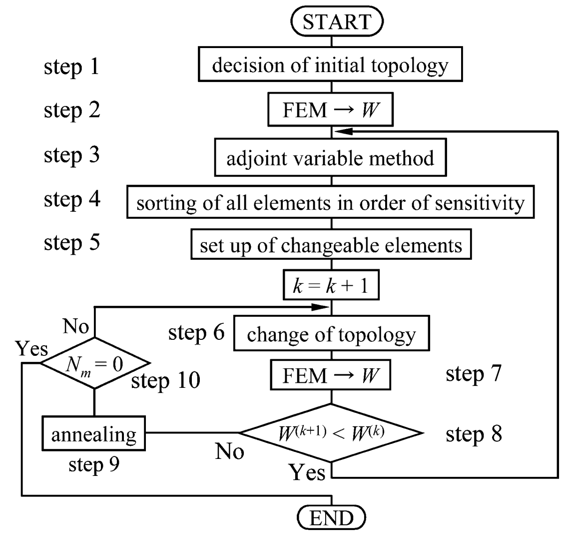

Fig. 2. Flowchart of ON/OFF method.

Equation (7) suggests that only one extra solution for the adjoint vector is sufficient to determine the sensitivity to all parameters, rather than obtaining each value per parameter, providing a computationally fast method for deriving the gradients.

B. Newton–Raphson Method Using Line Search

In order to take account of the nonlinearity of magnetization property of magnetic material, the Newton–Raphson method is applied. In the topology optimization, the convergence characteristic is worse because the various topology is generated. In order to improve the convergence characteristic and to decrease the number of iterations, the line search [10] is applied to the Newton–Raphson method.

A search direction $\delta \boldsymbol{A}^{(k)}$ of the magnetic vector potential at each nonlinear iteration k is calculated by using the ordinary Newton–Raphson method. Then, a step size $\alpha^{(k)}$ in the iterative process ($\boldsymbol{A}^{(k+1)} = \boldsymbol{A}^{(k)} + \alpha^{(k)}\delta \boldsymbol{A}^{(k)}$) is determined by the following equation:

$$\frac{\partial \chi^{(k+1)}}{\partial \alpha^{(k)}} = \left\{ \frac{\partial \chi^{(k+1)}}{\partial \boldsymbol{A}^{(k+1)}} \right\}^T \frac{\partial \boldsymbol{A}^{(k+1)}}{\partial \alpha^{(k)}} = \boldsymbol{R}^T \delta \boldsymbol{A}^{(k)} = 0 \quad (8)$$

where χ is the energy functional, $\boldsymbol{R}$ is the residual vector, and the superscript T means the transposition of a column vector. By assuming that $\boldsymbol{R}^T \delta \boldsymbol{A}^{(k)}$ can be approximated by a straight line, $\alpha_{\mathrm{app}}^{(k)}$ which satisfies (8) is calculated as shown in Fig. 1. By calculating $\boldsymbol{R}^T \delta \boldsymbol{A}^{(k)}$ at two points, for example $\alpha^{(k)} = 0.5$ and 1.0, the cross point α_{app} of the line $\boldsymbol{R}^T \delta \boldsymbol{A}^{(k)}$ is obtained. When the change of the flux density in each element is less than 10^{-3} T, the nonlinear iteration is terminated.

C. ON/OFF Method

The ON/OFF method [7] for avoiding the grayscale elements is effective for designing the practical magnetic circuit from the viewpoint of material arrangement in each element (magnetic material or air). The flowchart of the ON/OFF method is shown in Fig. 2.

Step 1: decision of initial topology
The initial topology in the design domain is decided by the material arrangement in each element.

Step 2 and Step 7: FEM $\rightarrow \boldsymbol{W}$
The objective function W of the design domain is obtained from the calculated value using FEM.

Step 3: adjoint variable method
Solving the adjoint equation (6), the sensitivity is calculated by using (7)

Step 4: sorting of elements in order of sensitivity
Each element is ranked in order of the absolute value of sensitivity.

Step 5: setup of changeable elements
If the sensitivity $\mathrm{d}W/\mathrm{d}\mu_{rk}$ with respect to permeability μ_k in element k is negative, the permeability in the element k should be increased. Then, the magnetic material is located in the element k. On the other hand, if the sensitivity $\mathrm{d}W'/\mathrm{d}\mu_{rk}$ is positive, the permeability in the element k should be decreased. Then, the air is allocated in the element k. In this step, the element, of which the state is changeable, is selected.

Step 6: change of topology
The topology is modified following the information obtained in Step 5.

Step 8: $\boldsymbol{W}^{(k+1)} < \boldsymbol{W}^{(k)}$
If the objective function $W^{(k+1)}$ is smaller than $W^{(k)}$, return to Step 3, otherwise go to step 9.

Step 9: annealing
If the objective function is not improved at all, the changeable elements N_m is decreased using the following equation:

$$N_m = \gamma \cdot N_m \quad (9)$$

where γ is the annealing factor, which is chosen as 0.9. Repeat Steps 6–9 until some improvement of the objective function is detected.

Step 10: $\boldsymbol{N_m} = 0$
If the number of changeable elements N_m becomes zero, the computation is terminated. Otherwise, return to Step 6.

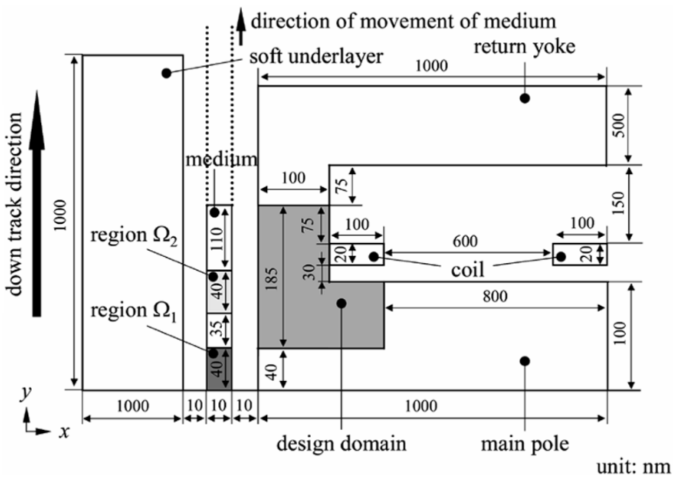

Fig. 3. Model of perpendicular head.

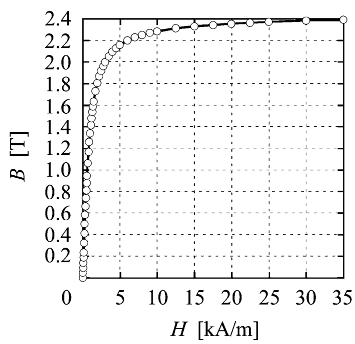

Fig. 4. Magnetization property of FeCoAlO.

Using the algorithm mentioned above, a fast convergence characteristic and a good topology can be obtained.

III. Analyzed Model and Objective Function

The analyzed model of the perpendicular magnetic recording system is shown in Fig. 3. FeCoAlO (saturated magnetization: $M_s = 2.4$ T) is adopted as the magnetic material of return yoke, soft underlayer, and design domain (modified return yoke for shielding and main pole). The magnetization property of FeCoAlO is shown in Fig. 4. The measured data is interpolated by a cubic function using the Akima's method. The quadratic approximation is applied until the saturation magnetization, and after saturation magnetic flux density, B is treated as a straight line directly proportional to magnetic field H. The current density in the coil is chosen as 0.1 A. The triangular elements of first order are adopted as element shape. The number of elements in design domain is set as 4002.

The design goal of this optimization problem is to maximize the flux density (recording flux) in the region Ω_1, and to minimize the flux density (leakage flux) in the region Ω_2 (adjacent bit) in the media. The function W_1 and W_2 in the regions Ω_1 and Ω_2 to be minimized are given as

$$W_1 = S_{\Omega_1} \sum_{ie=n_1}^{n_2} \frac{1}{B_x^{(ie)^2} \Delta^{(ie)}} \tag{10}$$

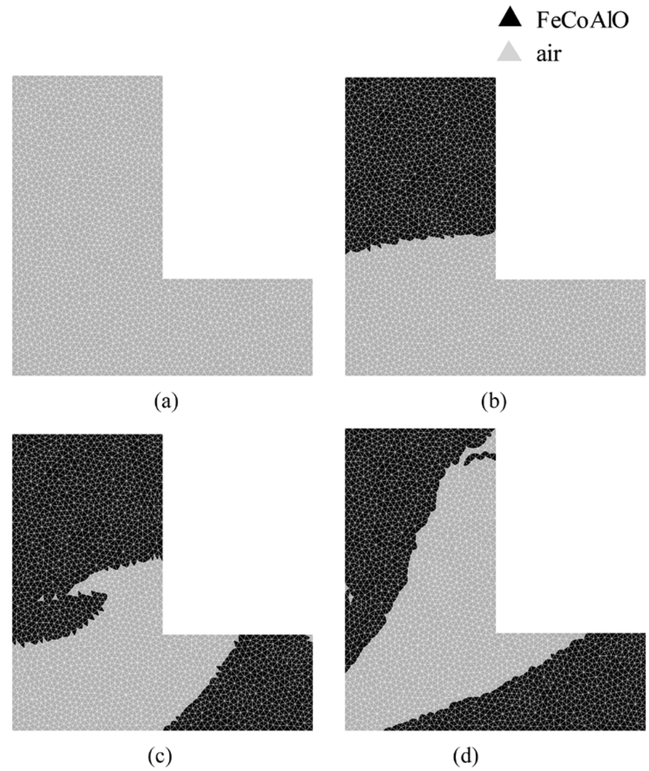

Fig. 5. Convergence process of optimal topology. (a) Initial state ($W_1 = 2.23 \times 10^3, W_2 = 0.22$). (b) First iteration ($W_1 = 2.86 \times 10^3, W_2 = 0.049$). (c) Second iteration ($W_1 = 2.33 \times 10^3, W_2 = 0.020$). (d) 40th iteration (optimal, $W_1 = 1.77 \times 10^3, W_2 = 0.0084$).

$$W_2 = \frac{\sum_{ie=l_1}^{l_2} B_x^{(ie)^2} \Delta^{(ie)}}{S_{\Omega_2}} \tag{11}$$

where $B_x^{(ie)}$ is the x-component of flux density in an element ie, $\Delta^{(ie)}$ is its area. S_{Ω_1} and S_{Ω_2} are the areas of regions Ω_1 and Ω_2. n_1 and n_2 are the starting number and the final number of the element in the region Ω_1, l_1 and l_2 are the starting number and final number of the element in the region Ω_2. Finally, in order to convert a multiobjective function into a single-objective function, the objective function W is defined as

$$W = k_1 W_1 + k_2 W_2 \tag{12}$$

where k_1 and k_2 are the coefficients to adjust the order of W_1 and W_2, respectively. In this problem, k_1 is chosen as 1.0 and k_2 is chosen as 2.0×10^4.

IV. Optimization and Discussion

The initial material of design domain is assumed as air. Fig. 5 shows the convergence process of optimal topology in design domain. An approximate shield topology is generated at the first iteration in order to prevent the leakage flux in the region Ω_1. At the second iteration, the main flux in the region Ω_1 is decreased so that the additional pole is generated in order to increase the flux in the region Ω_1. Finally, the optimal shape of shield and pole is generated at the 40th iteration. In this optimization, the number of iterations by using the line search Newton–Raphson

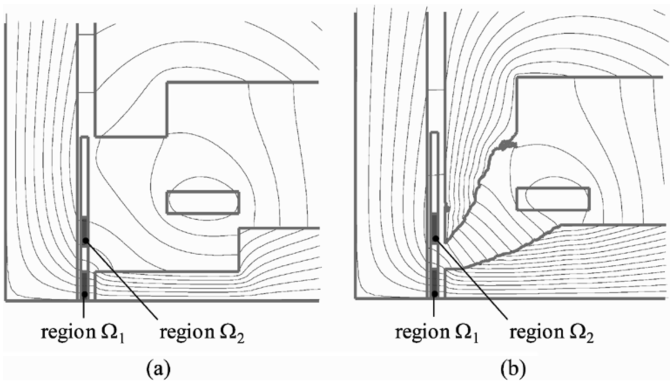

Fig. 6. Flux distributions. (a) Initial topology ($B_{1\,\max} = 1.65$ T, $B_{2\,\max} = 0.61$ T). (b) Optimal topology ($B_{1\,\max} = 1.90$ T, $B_{2\,\max} = 0.34$ T).

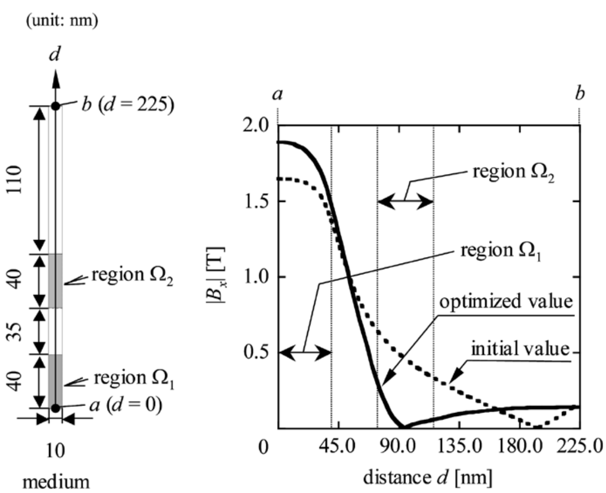

Fig. 7. Changes of magnetic flux density B_x on media on line a–b.

method is about 9, while the number of iterations is about 13 by using the ordinary Newton–Raphson method.

Fig. 6 shows the flux distributions of the initial and optimal topology. In the initial topology, the maximum flux density $B_{2\,\max}$ in the region Ω_2 is 0.61 T, because the leakage flux is generated from the main pole. The maximum flux density $B_{1\,\max}$ in the region Ω_1 is 1.65 T. By applying the topology optimization, $B_{2\,\max}$ is decreased, and $B_{1\,\max}$ is increased.

Fig. 7 shows the changes of $|B_x|$ on the centerline of medium a–b. The design goal in the region Ω_1 and region Ω_2 is performed. The maximum value of $|B_x|$ is 1.89 T at region Ω_1, and the minimum value of $|B_x|$ is 0.24 T at the region Ω_2 in the optimized value.

Fig. 8 shows the convergence process of the objective function. W_1 and W_2 are oscillating by the mutual effect around initial steps, but W is decreased steadily. The CPU time of 40 iterations is 1.6 h by using a PC (CPU: 2.8 GHz, RAM: 2.0 GB).

V. Conclusion

The paper presents an approach to design the perpendicular magnetic recording head for 200 Gb/in^2 by using the ON/OFF

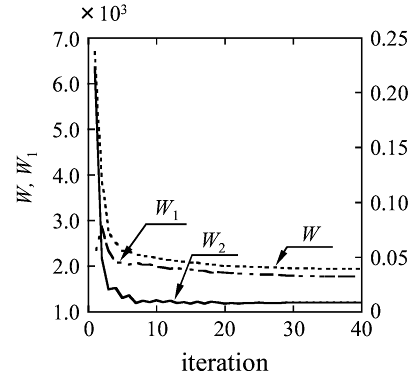

Fig. 8. Convergence process of objective function (CPU time: 1.6 h, CPU: 2.8 GHz, RAM: 1.5 GB).

topology optimization technique. In order to prevent the leakage flux density and to increase the main flux, the new topology of the magnetic shield and main pole is fully designed in two dimensions. As a result, the leakage flux is decreased, and the main flux is increased.

In order to produce an actual recording head having the optimal topology obtained by the ON/OFF method, the topology contour should be more feasible. The development of an effective topology smoother, and the 3-D topology optimization of the perpendicular magnetic recording head considering the read/write process are the future work.

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