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Optimal Design of the Optical Pickup Actuator Coil

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Key Words: Optical pickup actuator, Coil, Tilt motion, Sensitivity, Topology Optimization.

ABSTRACT

The objective of this work is to develop a new design method to find optimal coils, especially the optimal coil configuration of an optical pickup actuator. In designing actuator coils, the developed Lorenz force in the coils along the desired direction should be made as large as possible while forces and torques in other directions should be made as small as possible. The design methodology we are developing is a systematic approach that can generate optimal coil configurations for given permanent magnet configurations. To consider the best coil configuration among all feasible coil configurations, we formulate the design problem as a topology optimization of a coil. The present formulation for coil design is noble in the sense that the existing topology optimization is mainly concerned with the design of yokes and permanent magnets and that the optimization of actuator coils is so far limited within shape or size optimization. Though the present design methodology applies to any problem, the specific design example considered is the design of fine-pattern tracking and focusing coils.

I. INTRODUCTION

In designing a high-speed, high-performance optical pickup, the optimal design of the magnetic circuit of a pickup actuator is a very important issue. A typical magnetic circuit consists of a permanent magnet, a yoke, focusing and tracking coils. The actuating or driving forces developed in the coils are predicted by Lorenz's force equations. Though the tracking and focusing coils are supposed to generate forces only in the tracking and focusing directions, respectively, unwanted torques causing tilting motion are usually developed. Since tilting motions deteriorate actuator performance, the magnetic circuit should be carefully designed to minimize the resulting tilting motions, among others.

In this investigation, we are mainly concerned with the optimal design of focusing and tracking coils of fine pattern. Our idea to find the optimal coil configuration is to formulate the design problem as the topology optimization of a coil. There have been several attempts to design better magnetic circuits [1-5] for optical pickup actuators, but there is no topology optimization method yet developed for the coil problem in consideration. The specific design problem is to *find an optimal coil configuration to maximize the Lorenz force* along the desired direction and to minimize other forces and torques along the undesired directions. The coil mass will be also given as a constraint.

For the topology optimization of fine-pattern coils, the magnetic flux density is assumed to be known. This assumption is equivalent to fix the size and location of permanent magnets for the optimization problem. By three-dimensional magnetostatic analysis using the edge-based vector potential, we first determine the distribution of the magnetic flux density vector normal to the two-dimensional plane where the fine-pattern focusing and tracking coils are located. With the known magnetic flux density vector, the two-dimensional design domains of the coils are discretized by finite elements. To find the optimal coil configurations, the electric conductivity is penalized as a function of the element density design variable varying from 0 to 1. To find clear black and white images, the S-shaped mapping function used in [6,7] is employed. For *optimization iterations, the method of moving asymptotes* [8] *is* employed and the design sensitivity is performed by using the adjoint variable method [9]. To formulate the topology optimization of the coils, it is convenient to use the scalar potential approach developed in [10] for the electric field analysis.

II. PROBLEM DEFINITION AND FORMULATION

To propose an optimization formulation to design optimal focusing and tracking coils, it may be convenient to work with a specific model. In this work, we will be mainly concerned with fine-pattern coils as illustrated in Fig. 1. Figure 1(a) shows the schematic figure of an optical pickup having fine-pattern coils. As indicated in Fig. 1(b), coils generating forces in the focusing and tracking directions are patterned in a plane parallel to the x-y plane. Figure 1(c) shows the permanent magnetic configuration with its polarity indicated by N and S. From the magnetic configuration shown in Fig. 1(c), the magnetic flux density vector can be assumed to point in the z axis. Using the standard finite element procedure, one can determine the z-component B_z of the magnetic flux density vector **B**.

If electric current flows into coils located in the two-dimensional design domain, forces and torques generated in the coils can be calculated by Lorenz's force equations. If a complete coil contour is denoted by C and the current flowing in the coil, by I, the generated force **F** and torque **T** can be written as

$$\mathbf{F} = I\oint_C d\mathbf{l} \times \mathbf{B} = \int_V \mathbf{J} dV \times \mathbf{B} \qquad (1)$$

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$$\mathbf{T} = \mathbf{r}\times I\oint_C d\mathbf{l}\times\mathbf{B} = \mathbf{r}\times\int_V \mathbf{J}dV\times\mathbf{B} \tag{2}$$

where **J** denotes the current density vector and **r** is the position vector of a generic point in the coil from a certain origin such as the mass center. If the magnetic flux density vector is assumed to have only *z*-component, the non-vanishing components of **F** and **T** can be assumed to be F_x, F_y and T_z.

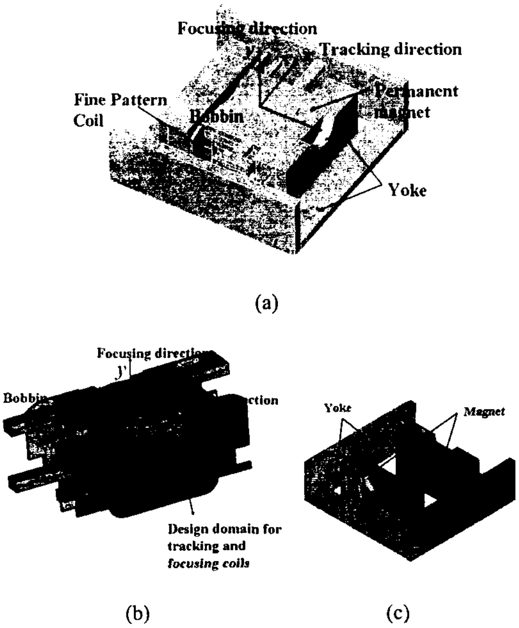
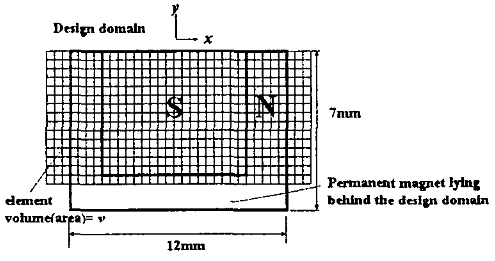
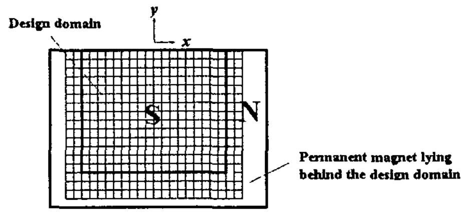


Fig.1. The schematic figure of an optical pickup actuator using fine-pattern coils (Coils are not drawn in the figure.)



(a) for tracking



(b) for focusing

Fig.2. Design domain discretization for the topology optimization of fine-pattern coils

For the topology optimization of fine-pattern coils, the two-dimensional design domain is discretized by finite elements as shown in Fig. 2. The coil configuration in design domain will be determined when design optimization is completed. If the coil configuration is given, the force F_x, and F_y in the *x* and *y* directions and the radial torque T_z can be expressed as

$$F_x = I\sum_{e=1}^{n_d}(l_{y\_eff}B_z)_e \tag{3}$$

$$F_y = I\sum_{e=1}^{n_d}(-l_{x\_eff}B_z)_e \tag{4}$$

$$T_z = -I(yl_{y\_eff}B_z + xl_{x\_eff}B_z) \tag{5}$$

where $(l_{y\_eff})_e$ and $(l_{x\_eff})_e$ denote the effective lengths of the *e*-th finite element, which may be determined by Eqs. (1-2).

For the topology optimization of the coil configuration, the coil is treated as an electric conductor having varying electric conductivity σ For a given distribution of the electric conductivity in the design domain, $(l_{y\_eff})_e$,*etc.* can be calculated by the using method described in [10].

Assigning one design variable ρ to each element, the electric conductivity σ is assumed as a function ρ as

$$\sigma = \sigma_0 f(\rho_e) = \frac{\sigma_0}{1+e^{-s(a\times\rho_e - b)}} \quad (i=1,\ldots n_d) \tag{6}$$
$$\text{with } 0<\rho_{\min}\le\rho_e\le\rho_{\max}\le 1$$

The common interpolation function $f(\rho_e)$ is ρ_e^n , but the sigmoid function of Eq. (6) [6,7] is employed to obtain clear white and black images. For all numerical calculations, the values of s=0.3, a=60, b=30 were used. The topology optimization definition for the design of fine-pattern tracking and focusing coils is as follows:

Tracking Coil Design

Minimize:

$$f_t(\boldsymbol{\rho}) = w_t^y\left|\frac{F_y}{\overline{F}_y}\right| - w_t^x\left|\frac{F_x}{\overline{F}_x}\right| + w_t^z\left|\frac{T_z}{\overline{T}_z}\right| \tag{7a}$$

Subject to:

$$h(\rho_e) = \sum_{e=1}^{n_d}\rho_e v_e - M_t^0 \le 0 \tag{7b}$$

$$0<\rho_{\min}\le\rho_e\le\rho_{\max}\le 1 \tag{7c}$$

Focusing Coil Design

Minimize:

$$f_f(\boldsymbol{\rho}) = -w_f^y\left|\frac{F_y}{\overline{F}_y}\right| + w_f^x\left|\frac{F_x}{\overline{F}_x}\right| + w_f^z\left|\frac{T_z}{\overline{T}_z}\right| \tag{8a}$$

Subject to:

$$h(\rho_e) = \sum_{e=1}^{n_d} \rho_e v_e - M_f^0 \le 0 \qquad (8b)$$

$$0 < \rho_{\min} \le \rho_e \le \rho_{\max} \le 1 \qquad (8c)$$

In Eqs. (7a-8a), the barred quantities such as $\bar{F}_x$, $\bar{F}_y$ and $\bar{T}_z$ are introduced to non-dimensionalize unbarred quantities. For the present work, the barred quantities are evaluated with an initial uniform density distribution $\rho_e = M^0 / v$, where M^0 is the prescribed mass and v is the volume (actually area) of the design domain. The parameters $w_\alpha^\beta (\alpha = t, f;\ \beta = x, y, z)$ are the weighting factors for the contribution of F_x, F_y and T_z in the objective functions. The detailed description of the topology optimization of coils is given in [11].

III. OPTIMIZED COIL CONFIGURATION

In the section, optimized tracking and focusing coils will be prescribed. The followings are the data used for the design of tracking and focusing coils.

Fine-Pattern Tracking Coil Design Optimization

- mass constraint: 28% of original design domain
- number of finite elements: n_e =4096

(due to the symmetry require about the y axis, only half of the design domain is discretized)

- initial guess ρ_e=0.28 (also used to calculated $\bar{F}_x, \bar{F}_y, \bar{T}_z$)
- $w_t^x = 1, w_t^y = 0.01, w_t^z = 1$

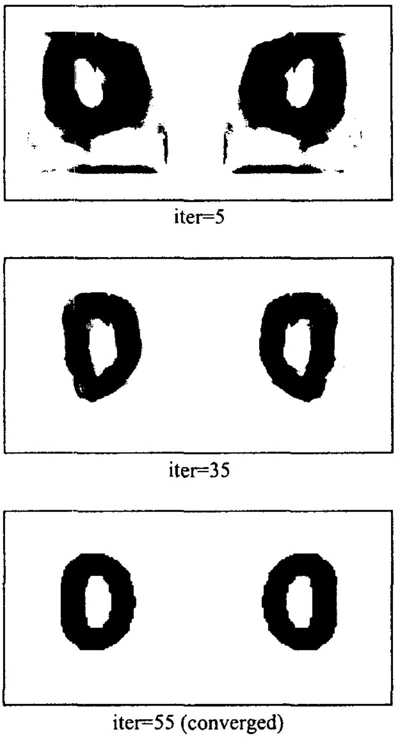
Fine-Pattern Focusing Coil Design Optimization

- mass constraint: 16% of original design domain
- number of finite elements: n_e =4096
- initial guess ρ_e=0.4

(also used to calculated $\bar{F}_x, \bar{F}_y, \bar{T}_z$)

- $w_f^x = 0.01, w_f^y = 1, w_f^z = 1$

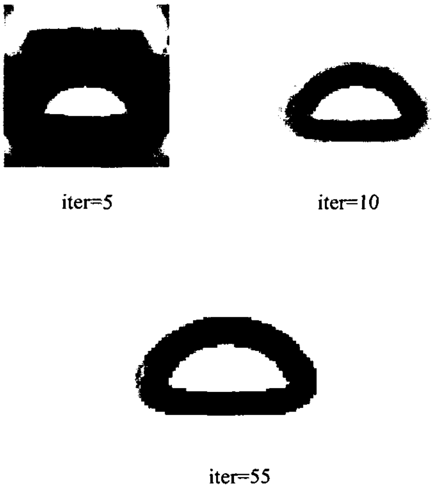
Figures 3 and 4 show the optimized results for the tracking and focusing coils. Figure 5 compares the present optimized coil configuration with that by Pioneer. They have the same topologies, but the shapes are somewhat different. The performance of the coils in Fig. 5 may be best compared in terms of their sensitivity. Assuming the same current flowing into the coil, the resulting forces and torques for both coil configurations are calculated. The results are summarized as Tables I and II. Although the improvement by the present model over the existing model is not substantial, the present methodology is very effective to generate optimal coil configurations without many "manual" trial and errors.


iter=5

iter=35

iter=55 (converged)

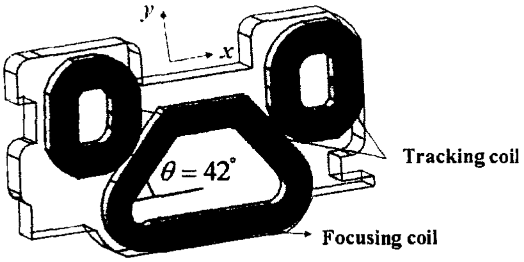
Fig. 3. The optimized results for the tracking coil during the topology optimization iterations (iter=the optimization iteration number)


iter=5

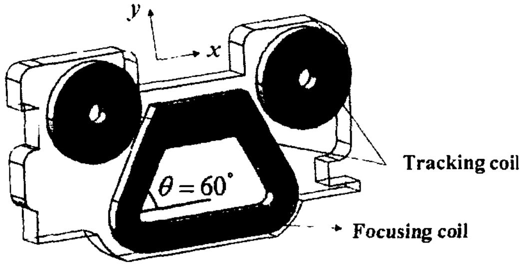
iter=10

iter=55

Fig. 4. The optimized results for the focusing coil during the topology optimization iterations (iter=the optimization iteration number)



(a) present



(b) by Pioneer

Fig. 5. Comparison of the present optimized coil configuration with that by Pioneer

Table I. Performance comparison of the tracking coils by the present model and the Pioneer model

Pioneer model			Present		
Fx (desired)	*Fy* (unwanted)	*Tz* (unwanted)	*Fx*	*Fy*	*Tz*
-4.41	0.0399	0.194	-5.10	0.0203	0.127

Table II. Performance comparison of the focusing coils by the present model and the Pioneer model

Pioneer model			Present		
Fx (unwanted)	*Fy* (desired)	*Tz* (unwanted)	*Fx*	*Fy*	*Tz*
-0.0048	5.8446	0.0322	-0.0013	5.997	0.0382

(Force unit: mN , Torque unit: mN · mm)

IV. CONCLUSIONS

This investigation is concerned with a new topology optimization formulation for optimal coil design, especially the design of the coils used in optical pickup actuators. There were some attempts to carry out the topology optimization of magnetic circuits, but the existing researches were mainly focused on the design of yokes, permanent magnets, and some coils with the fixed current density field. In the present research, the current density field is formulated to vary, so the coil topology optimization can be formulated to maximize the Lorenz force along the desired direction and minimize forces and torques in other directions. The specific application of the present methodology is made to the design of fine-pattern coils, and the optimized focusing and tracking coils by the present method turned out to be very similar to the commercially available coils, with slight performance improvement. However, the point of this research is not that designs similar to the exiting designs can be obtained by the present methodology, but that a new topology optimization formulation applicable for any coil design, especially for the design of optical pickup actuator coils, is now established.

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