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Topology Optimization of a HDD Actuator Arm

Su-Young Chang, Ji-Hyon Cho, Sung-Kie Youn,† Cheol-Soon Kim,[1] and Dong-Ho Oh[1]

Department of Mechanical Engineering, KAIST, 373-1, Kusung,Yusung, Taejon, 305-701, Korea
[1] Electro Mechanics Lab, System & Control Sector, SAIT, P. O. Box 111, Suwon, 440-600, Korea

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ABSTRACT

A study on the topology optimization of a Hard-Disk-Driver(HDD) actuator arm is presented. The purpose of the present work is to increase the natural frequency of the first lateral mode of the HDD actuator arm under the constraint of total moment of inertia, so as to facilitate the position control of the high speed actuator arm. The first lateral mode is an important factor in the position control process. Thus the topology optimization for 2-D model of the HDD actuator arm is considered. A new objective function corresponding to multieigenvalue optimization is suggested to improve the solution of the eigenvalue optimization problem. The material density of the structure is treated as the design variable and the intermediate density is penalized. The effects of different element types and material property functions on the final topology are studied. When the problem is discretized using 8-node element of a uniform density, the smoothly-varying density field is obtained without checker-board patterns incurred. As a result of the study, an improved design of the HDD actuator arm is suggested. Dynamic characteristics of the suggested design are compared computationally with those of the old design. With the same amount of the moment of inertia, the natural frequency of the first lateral mode of the suggested design is subsequently increased over the existing one.

Keywords: topology optimization, eigenvalue, Hard-Disk-Driver (HDD), moment of inertia

1. Introduction

In order to increase the speed of HDD, the seek time needed for HDD actuator head to locate the position of data on the disk, must be shortened. If the driving frequency of the HDD actuator arm goes near to the natural frequencies of the lateral eigenmodes, it is difficult for the HDD actuator arm to be controlled in the rotary direction. At this place, the lateral eigenmode is the eigenmode moving on the plane perpendicular to the axis of rotation of the HDD actuator arm. To avoid the above mentioned difficulty, the natural frequency of the first lateral eigenmode should be increased, so as for this to get away from the driving frequency. Also if the moment of inertia of the HDD actuator arm is increased to increase the natural frequency, the movement of the HDD actuator arm with fixed power source will be slow in action. Therefore, to achieve the improvement of the position control, the natural frequency of the first lateral eigenmode of the actuator arm should be increased while the moment of inertia is kept minimum.

The optimization methods of structure can be classified into size, shape and topology optimization. The topology optimization method defines the region, in which the design change is required, as design domain and finds the material existence in each part of the design domain.

The topology optimization of a continuum structure was firstly attempted by Bendsoe and Kikuchi (1988). To find the relationship between the macroscopic material properties and the material density, Bendsoe and Kikuchi (1988) introduced the microstructure with a rectangular hole and applied the homogenization method. Bendsoe (1989) introduced the rank-2 material as a microstructure. Suzuki and Kikuchi (1989) applied this approach to the optimization of structures under static loading conditions. Diaz and Kikuchi (1992) and Ma, Kikuchi and Hagiwara (1992) applied this approach to the free vibration problem and the frequency response problem respectively. Diaz

†Corresponding author
Tel.: +82-42-869-3034; Fax: +82-42-869-3210
E-mail address: skyoun@sorak.kaist.ac.kr

and Belding (1993) applied the modified approach to the truss structure problem. Bendsoe, Diaz and Kikuchi (1993) formulated the optimization problem with various load and boundary conditions. Jog (1996) applied this approach into the non-linear thermoelasticity problem. Jog and Haber (1996) explained the cause of the unstable solution such as checker-board patterns.

In the present work, by using topology optimization method, the new design of HDD actuator arm is suggested, in which the natural frequency of the first lateral mode is significantly increased while the moment of inertia is kept below that of the old design. A new objective function corresponding to multieigenvalue optimization problem is suggested to improve the solution of the eigenvalue optimization problem and the constraint condition for restricting the moment of inertia is imposed. The algorithm (1993), which is devised considering the features of the dynamic problems like free vibration, is utilized and the validity of the solution acquired by this algorithm is investigated. By taking advantage of the shape features of HDD actuator arm and the fact that the first lateral mode is an important factor in the position control process, a 2-D model of the arm is considered for the topology optimization. As a result of the above study, an improved design of the HDD actuator arm is suggested. Dynamic characteristics of the suggested design are compared computationally with those of the old design through the 3-D eigenvalue analysis.

2. Topology Optimizaion Method

2.1 Fundamental concepts

The shape of the structure can be represented by parametrization of the boundary of the structure or by indicator function. By the former, the topology of the structure cannot be changed during the optimization process, so it is difficult to obtain the truly optimized structure through the optimization process. But if the latter is used, the truly optimized structure can be obtained.

In the present work, the material density approach is used for the topology optimization.

At the initial state of applying the topology optimization, the following indicator function is introduced:

$$\chi(x) = \begin{cases} 1 \text{ if } (x \in \Omega^m) \\ 0 \text{ if } (x \notin \Omega^m) \end{cases} \tag{1}$$

where Ω^m is the region occupied by the material.

By using Eq. (1), the elasticity tensor at the point x, E_{ijkl} be represented as following:

$$E_{ikl}(x) = \chi(x)E^m_{ijkl} \tag{2}$$

where E^m_{ijkl} is the elasticity tensor of the material.

If we want to find the optimized shape of the structure by using the indicator function, we must find the indicator function value at all points in the structure. But in general, the existence of the solution of the problem is not guaranteed, since the indicator function is not smooth, (Korn RV and Strang G, 1986). The need for the relaxation of the problem using the homogenization therefore arises. By introducing the concept of the material density instead of using the indicator function, the generalized shape optimization problem can be stated as finding the material density at all points in the structure. Considering the computational cost during the optimization process, the structure is divided into a finite number of elements and the material density in each element is sought through the optimization process. It is assumed that the material density in an element is uniform.

If we use the material density χ, which can have a value between 0 and 1, we must obtain the functional relationship between the elastic moduli and the material density. The functional relationship between the elastic moduli and the material density can be obtained by several methods. One is to apply the homogenization method after introducing a microstructure. Another is to use a artificial material model, which relates arbitrarily the elastic moduli to the material density without introducing any specific microstructure. The former has been used since Bendsoe and Kikuchi (1988) had used it firstly. But the patterns of the optimal density distributions depend strongly on the microstructure employed. Also it needs a additional finite element analysis to obtain the homogenized material properties. Although the latter is very simple, the solution quality obtained by this is competitive with that obtained by the former if the adequate functional relationship is used (Yang and Chuang 1994; Youn and Park (1997).

In the present work, the following artificial material model, Youn and Park (1997), which is based on the Hashin-Shtrikman lower bound, is used.

$$E_{ijkl} = \frac{x_e}{(1+\alpha\times(1-x_e))}E^m_{ijkl} \tag{3}$$

where x_e is the material density in the e-th element and α a constant, with which the intermediate density is differently penalized. In Eq. (3), α is chosen as 20, with which the convergence of the optimization process is satisfactory. Figure 1 shows the functional relationship between Young's Modulus and material density, ρ. In Fig. 1, the line, $y=x$, indicates the upper bound of the material property of the intermediate density material.

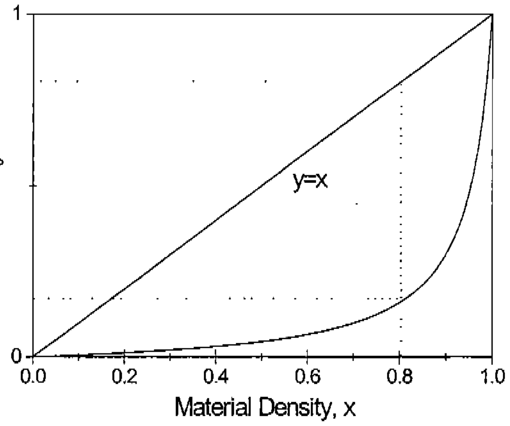


Fig. 1. Functional relationship between Young's Modulus and material density, x.

2.2 Definition and formulation of the optimization problem

After introducing the concept of the material density, the topology optimization problem can be stated as the usual optimization problem. The material densities in elements, which the structure is divided into, is treated as the design variables.

$$\begin{aligned} &\textit{Minimize} \quad f(X) \\ &\textit{subject to} \quad h_i(X) \le 0,\ 1 \le i \le M \\ &\qquad\qquad\quad g_j(X) \le 0,\ 1 \le j \le N \end{aligned} \tag{4}$$

where $X = [x_1, x_2, \ldots, x_{n_{el}}]^T$ is the design variable vector and n_{el} is the number of elements in the design domain.

The Objective function and constraint conditions in Eq. (4) can be defined differently depending on the purpose of optimization. The purpose of this research is to increase the natural frequency of the first lateral mode of the HDD actuator arm under the constraint of total moment of inertia. So the objective function and the constraint condition can be defined as follows:

$$f(X) = \frac{1}{\sum_{i=1}^{n} (c_i(\lambda_i/\lambda_{0i}))} \tag{5}$$

where n is the number of weighted eigenvalues, λ_i the i-th eigenvalue of the structure at the current step, λ_{0i} the i-th eigenvalue of the structure for which the entire design domain is filled with the given material and $\sum_{i=1}^{n} c_i = 1$.

$$h(X) = \int_\Omega \rho d^2 d\Omega - I_0 \approx \sum_{c=1}^{n_{el}} \rho_{0e} \chi_e d_e^2 \Omega_0 - I_0 \le 0 \tag{6}$$

where Ω is the fixed design domain, ρ the density, d the distant from the rotating center of the structure, I_0 the specified limit of moment of inertia, ρ_{0e} the density of material in the e-th element, χ_e the material density ($0 \leqq \chi_e \leqq 1$), d_e the distant from the rotating center of the structure to the center of the e-th element and Ω_e the area or volume of the e-th element.

The objective function (Eq. (5)) is constructed as the inverse of the weighted sum of the eigenvalues of the structure, considering the mode switching phenomena[13] during the optimization process. Usually in the eigenvalue optimization problem, when one maximizes a lower eigenvalue, higher eigenvalues may fall down to the lower values, It means that the order of the modes may be changed during the optimization process. In order to overcome this problem, the objective function is constructed as the weighted sum of the first n eigenvalues, within which the target eigenvalue of the optimization problem is always contained during the optimization process. Thus while the weighted sum is increased, the target eigenvalue of the optimization problem is also increased. In order to increase the target eigenvalue efficiently, the weighting coefficients of eigenvalues are chosen properly. The weighting coefficients of modal order, within which the target eigenvalue is anticipated during the optimization process, must be larger than the others. In Eq. (5), each eigenvalue λ_i is normalized by λ_{0i}, so that the contribution of each eigenvalue to the objective function will not depend on the absolute value of the eigenvalue. Because at all optimization steps except several at the beginning, the eigenmode of the computed structure is similar to the eigenmode of the structure for which the entire design domain is filled with the given material, the eigenvalue λ_i is normalized by λ_{0i}.

The eigenvalue of the structure is calculated by the finite element method. The sensitivities of the objective function and the constraint condition (Eq. (7) and Eq. (10)) can be calculated analytically by direct differentiation against the design variable, x_e (Ma *et al.* 1995).

$$\frac{\partial f}{\partial x_e} = -\left\{ \sum_{i=1}^{n} \left[c_i \cdot \left(\frac{1}{\lambda_{0i}}\right) \cdot \frac{\partial \lambda_i}{\partial x_e} \right] \right\} \cdot f^2 \tag{7}$$

$$\frac{\partial \lambda_i}{\partial x_e} = \phi_i^T \cdot \left(\frac{\partial K}{\partial x_e} - \lambda_i \frac{\partial M}{\partial x_e}\right) \cdot \phi_i \cdot \phi_{i,e}^T \cdot \left(\frac{\partial k_e}{\partial x_e} - \lambda_i \left(\frac{\partial m_e}{\partial x_e}\right)\right) \cdot \phi_{i,e} \tag{8}$$

where K is the global stiffness matrix, M the global mass matrix, k_e the e-th element stiffness matrix, m_e the e-th element mass matrix, λ the eigenvalue, ϕ_i the full eigenvector and $\phi_{i,e}$ the e-th element eigenvector.

$$\frac{\partial k_e}{\partial x_e} = \int_{\Omega_e} B_e^T \frac{\partial D_e}{\partial x_e} B_e d\Omega, \frac{\partial m_e}{\partial x_e} = \int_{\Omega_e} \frac{\partial \rho_e}{\partial x_e} N_e^T N_e d\Omega \tag{9}$$

where B_e is the strain shape function, D_e the effective stiffness, N_e shape function and ρ_e mass density.

$$\frac{\partial h}{\partial x_e} = \rho_{0e} \Omega_e d_e^2 \tag{10}$$

2.3 Optimization algorithm

The number of design variables of the present optimization problem is very large since fine finite element meshes are required to manage the resolution of the shape of the structure. On the other hand, the constraints of the present problem are simple. Therefore the optimality criteria method is adequate as updating rule for optimization problem in this category.

Although the updating rule which is based on the optimality suggested by Bendsoe and Kikuchi[1)], is very simple and efficient for the static problems, it does not work well in the dynamic case. For the static problems, the sensitivities of the objective function with respect to design variables, i.e., the material density in elements, is all negative. In other words the objective function is always decreased by increasing the material density of elements in the design domain of the structure. But for the dynamic problems like free-vibration, the sensitivities of the objective function about design variables can be negative or positive in elements. Considering the above feature of the dynamic problem, Ma, Kikuchi and Hagiwara (1993) proposed a new algorithm, which is derived by using a new convex generalized-linearization approach via a shift parameter which amounts up to the Lagrange multiplier and the use of the dual method. In the present work, the algorithm proposed by Ma, Kikuchi and Hagiwara (1993) is used.

Fig. 2 shows schematically the optimization process including the concrete method used in each stage.

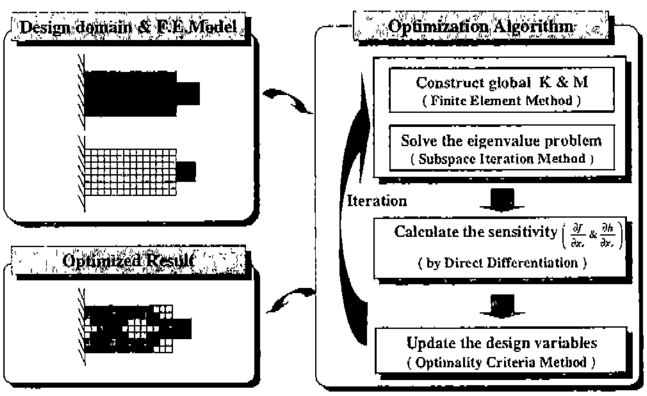


Fig. 2. Optimization process.

3. Application to the HDD Actuator Arm Design

3.1 The shape of HDD actuator arm and design requirements

Fig. 3 shows the shape of a HDD actuator arm, for which design modification is required. The requirements of design modification is that the first lateral natural frequency must be increased while the moment of inertia is kept below that of the existing design, as mentioned in section 1.

3.2 The application of the topology optimization method

The shape features of HDD actuator arm (Fig. 3) is that the thickness is discretely uniform from VCM to head. The target eigenmode of optimization, which is the first lateral eigenmode, moves only on the plane perpendicular to the rotating axial direction. Thus in the present work the topology optimization for 2-D model of HDD actuator arm is carried out, so that the required computational cost during the optimization process is subsequently diminished without significant degradation of the optimization results.

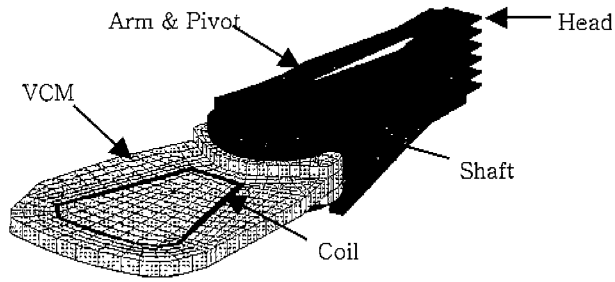


Fig. 3. The shape of HDD actuator arm.

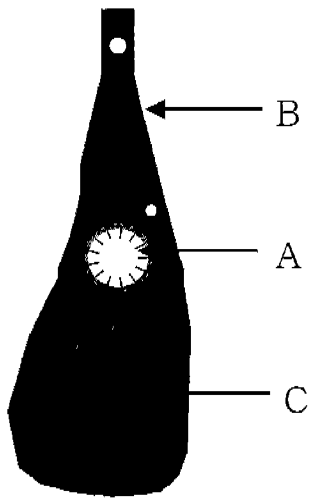


Fig. 4. 2-D model of the HDD actuator arm for optimization

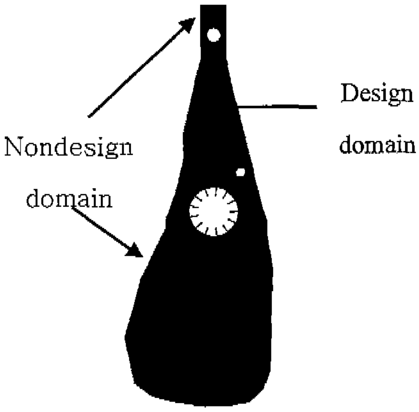


Fig. 5. The design domain (Arm part).

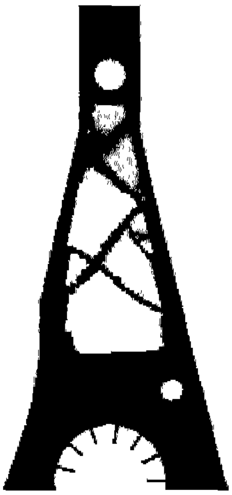


Fig. 6. The optimized material distribution (Arm part).

Fig. 4 shows the 2-D model of the HDD actuator arm, for which the optimization process is carried out. In Fig. 4, the material properties in each part of 2-D model is discriminated with different grade of shading. In each part, the Young's moduli and densities are defined as the real material properties multiplied by the thickness and the poisson ratios is defined as the same value of the real materials. The Part A in Fig. 4. is linear spring elements that model the ball bearing, considering the number of balls in the axial direction and contact angle with the body. The Part B in Fig. 4 is the arm part of the actuator arm, which is defined as the design domain of the first optimization process. The Part C in Fig. 4 is the VCM part inside the coil, which is defined as the design domain of the second optimization process. The boundary condition in Fig. 4 is that the inner points of all linear spring elements are fixed.

The objective function (Eq. (5)) is constructed with the following weighting coefficient for each eigenvalue.

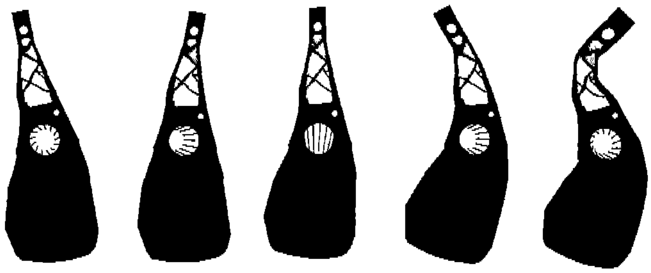


Fig. 7. The shapes of the first five eigenmodes.

Because the first eigenmode of the structure in Fig. 4 is rigid body mode, c_1 equal to zero. The first lateral eigenmode, which is target eigenmode of optimization, is anticipated as the second eigenmode of this structure. Therefore c_2 is relatively larger than others. Considering the mode switching phenomena, three modes are added as a safety measure (c_3, c_4 and c_5 ; refer Fig. 7).

c_1=0.0000, c_2=0.6250, c_3=0.1875, c_4=0.1250 and c_5=0.0625

The structure is discretized using 8-node elements. The initial design distribution is uniform in the whole design domain. Usually, the use of 4-node elements results in the unstable solutions like checker-board patterns, which are difficult to interpret. To overcome this difficulty, the several strategies were proposed. One is to apply a density redistribution algorithm while still using 4-node elements of a uniform density (Youn and Park, 1997). Another is to use 8-node elements with which the stable solutions are obtained without a specially contrived algorithm. If 8-node elements are used to discretize the structure, the computational cost required in analysis of the structure is increased, but the solution is much more credible.

In the present work, the arm part of HDD actuator (Part B in Fig. 4) is defined as a design domain (Fig. 5). The maximum value of the moment of inertia is constrained to have smaller value than that of the old design. The optimized material distribution in Fig. 6 represents a truss-like structure. Fig. 7 shows the eigenmode shapes of the optimized structure. Fig. 8(a) and Fig. 8(b) show the history of the objective function and the weighted natural frequencies respectively, during the optimization process. Fig. 9 shows the convergence of the material distribution during the optimization process. In Fig. 9, Niter means the number of iterations. Table 1 shows the natural frequen-cies of the optimized structure.

As shown in Fig. 8, the objective function is monotonically decreased. Although, in this case, the mode

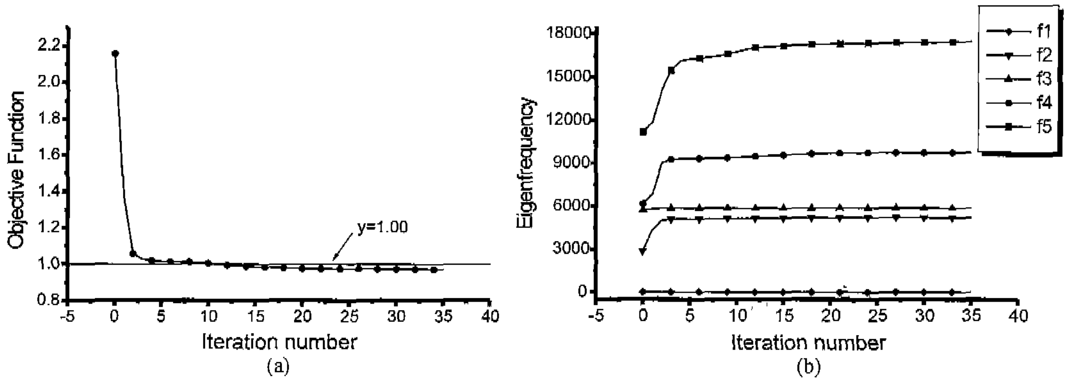
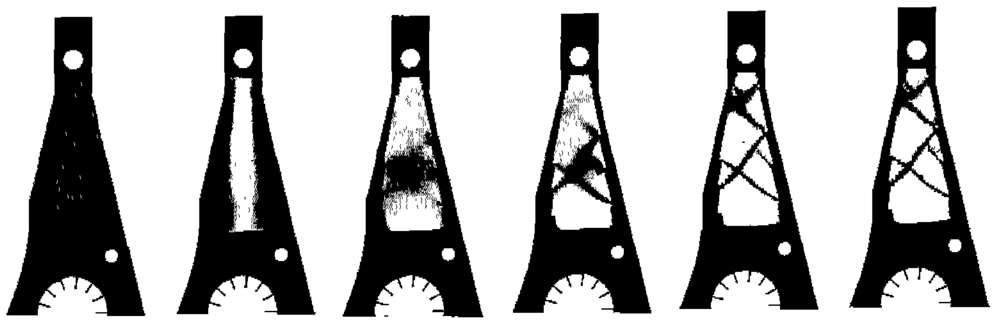


Fig. 8. The history during optimization process.



Initial Niter=1 Niter=5 Niter=10 Niter=20 Niter=35

Fig. 9. The converging process of the material distribution during the optimization process.

Table 1. Natural frequencies of the optimized structure

Function	Natural frequency (Hz)					Objective
	f_1	f_2	f_3	f_4	f_5	
Initial design	0	2863	5783	6170	11205	2.1555
Optimal design	0	5212	5904	9807	17611	0.9700
Reference Values (f_{0i})	0	5083	5607	10474	18556	–

Where reference values (f_{0i}) are the natural frequencies of the structure for which the entire design domain is filled with the given material.

Table 2. The optimized results under the four different constraints of the moment of inertia

Case	Natural frequency (Hz)					Objective Function
	f_1	f_2	f_3	f_4	f_5	
(a) I_0=33.81	0	5260	6069	9087	15126	1.0128
(b) I_0=34.71	0	5344	6022	9536	16197	0.9780
(c) I_0=35.61	0	5314	5988	9653	16829	0.9802
(d) I_0=36.51	0	5284	5965	9725	17508	0.9822
Reference Value (f_{0i})	0	5218	5928	9697	17663	–

switching did not occurred, it happened in other numerical experiments. However it did not affect the convergence of the optimization process.

In Fig. 9, the initial material distribution is uniform under the constraint of total moment of inertia.

As shown in Table 1, the target natural frequency f_2, whose value is 2863 Hz at the initial state before optimization, is increased to 5212 Hz after the optimization. With

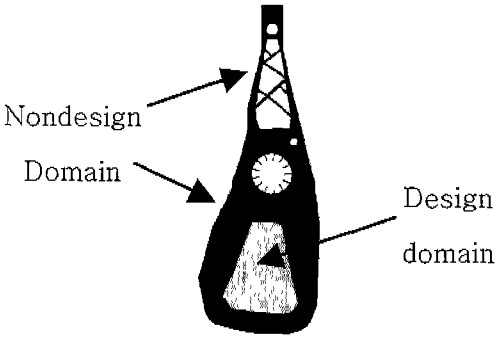


Fig. 10. The design domain (VCM part inside the coil).

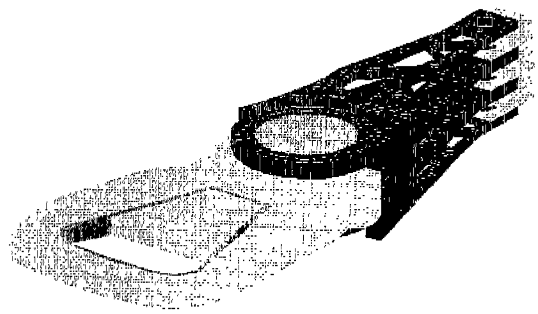
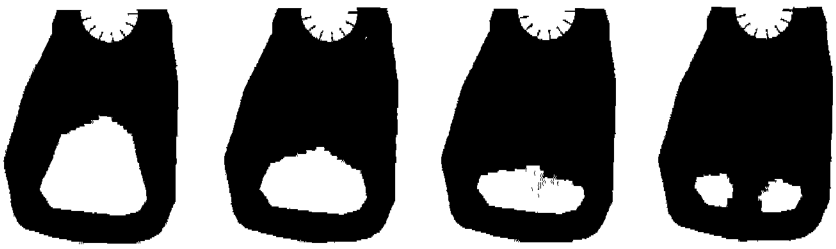
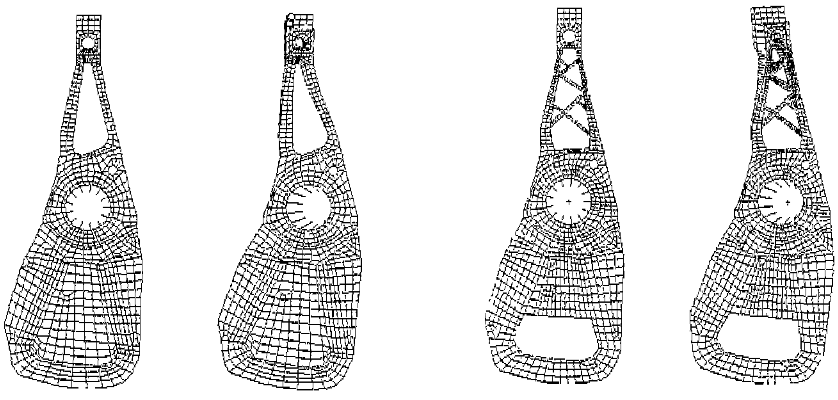


Fig. 12. The suggested design of the HDD actuator arm.



(a) $I_0 = 33.81$ (b) $I_0 = 34.71$ (c) $I_0 = 35.61$ (d) $I_0 = 36.51$

Fig. 11. The optimized material distribution (VCM part inside the coil).



Shape   Eigenmode   Shape   Eigenmode

(a) The conventional design   (b) The suggested design

Fig. 13. The shape of the structure and first lateral eigenmode.

previously optimized Part B fixed, the VCM part of HDD actuator (Part C in Fig. 4) is newly defined as design domain (Fig. 10). Through applying optimization to this new design domain, the final design, which has less moment of inertia than that of existing design, is obtained. Fig. 11 and Table 2 show the optimized results under the constraints of the four different values of the moment of inertia. As shown in Table 2, the case (b) in Fig. 11, is the most satisfactory result, because the target natural fre-quency of the optimization is the largest among all cases, although the moment of inertia in this case is relatively small.

3.3 Design suggestion

Based on the topology optimization results, the new design of HDD actuator (Fig. 12) is suggested. Fig. 13(b) shows the structure shape and the first lateral eigen-mode of the suggested design, while Fig. 13(a) shows those of the conventional design. The first lateral eigen-mode of the suggested design is occurred at the 14th and the frequency is 5152 Hz, while the first lateral eigenmode of the conventional design is occurred at the 10th and the frequency is 4721 Hz. But the moment of inertia of the conventional design and the suggested design are 38.29 and

33.90 (g · cm^2) respectively. So the suggested design reveals the larger first lateral natural frequency and the smaller moment of inertia.

4. Conclusions

In the present work, the topology optimization of HDD actuator arm with newly suggested objective function to improve the eigenvalue of the structure under the constraint on the moment of inertia of the structure, is presented, so as to facilitate the position control. The structure is discretized using 8-node elements of a uniform density, so that the smoothly-varying density field is obtained without checker-board patterns incurred. An artificial material model, whose elastic moduli are contrived to stay close to the lower side of the Hashin-Shtrikman bounds, is used to obtain the efficient relationship between effective elastic moduli and the density of the given material, so that the material distribution obtained by optimization has the least number of the intermediate density elements. The optimization for 2-D model of HDD actuator arm, which reflects the feature of the HDD actuator shape and lateral eigenmode, is carried out and then considering the result for 2-D model, the new design for HDD actuator is proposed. The new design of HDD actuator has a larger first lateral natural frequency but a less moment of inertia than that of the conventional design, because the topology optimization method can optimize the shape and topology of the structure during the optimization process simultaneously.

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