New Designs of HDD Air-Lubricated Sliders Via Topology Optimization

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Optimization is an efficient tool for developing designs of slider air bearings that meet the strict performance demands of current hard disk drives. Previous studies in this field concentrated on determining the optimal size and shape of the air-bearing surface for a specified initial design. The resulting optimal design has the same topology as that of the initial design. Therefore, the performance of the final optimal solution depends strongly on the initial design, which is chosen either intuitively or inspired by already existing designs. In this study, a topology optimization method is developed for determining the optimal slider configuration. First, the air-bearing surface is discretized by a uniform mesh. The optimization consists in determining whether the material contained in each element should be removed or not. Then, a genetic algorithm is employed for the determination of the optimal solution from the possible candidates. An example is presented to demonstrate the effectiveness of the proposed approach. The resulting optimal design has a topology different from those of the initial designs and possesses improved performance. [DOI: 10.1115/1.1631016]

Introduction

Due to the demand of higher data storage density for computer hard disk drives, the head-disk spacing has necessarily decreased significantly. The flying heights of current commercial sliders are in the range of 20–30 nm or below. Besides the extremely low spacing, it is also desirable to have a constant flying height over the entire disk, a low take-off/landing velocity, and a stiff air bearing [1]. Developments in slider manufacture techniques such as photolithography and plasma etching have made it feasible to produce arbitrary air-bearing surface geometries. With this control of geometry, many different sliders with complicated air-bearing surface (ABS) have been proposed for meeting the strict performance requirements. Consequently, the subsequent problem is to determine the optimal configuration of the air-bearing surface.

Several methods have been presented to obtain the optimal configuration subjected to different cost functions. Yoon and Choi [2] presented a new design of taper-flat sliders using an optimization technique, which considered the steady-state flying performance of the slider. O'Hara and Bogy [3] employed genetic algorithms and simulated annealing for the determination of the optimal design of a transverse pressure contour (TPC) slider. They considered the minimization of the variation in flying height over the radius of the disk. Lu et al. [4] presented an optimal design of a negative pressure slider using the simulated annealing. The cost function was defined as the variation in the flying heights at three different radii plus the difference of the mean value of these three flying heights and the target flying height. O'Hara et al. [5] employed the simulated annealing method to optimize a 25 nm flying height slider. The design goals were to maintain a specified flying height, to minimize the roll angle, and to decrease the sensitivity of the bearing to external loading. Yoon and Choi [6] used the sequential quadratic programming method for determining the optimal configuration of a TPC slider. The objective of optimization was to minimize the variation in flying height, to maximize the pitch angle and to keep the roll angle as small as possible. Kang et al. [7] presented new designs of air-bearing surfaces that reduce the flying height variation during the track seek as well as in steady state. They employed the method of modified feasible directions and used the weighting method to solve the multicriteria optimization problem.

The above methods for determining the optimization configuration of the air-bearing surface have a common feature: In order to initialize the optimization procedure, an original design of the air-bearing surface has to be proposed first. Then, some design variables that characterize the air-bearing surface, such as the vertices of the rail, the recess depth, and the pivot position, are specified. Finally, some optimization method is used to determine the set of design variables that minimizes the specified cost function. No matter how the design variables are changed, a rail will not break into two disjoint rails and no new cavities will emerge. Hence, the final design will have the same topology as that of the original design. In other words, these optimization techniques only change the shape and size of the initial design of the air-bearing surface. As a result, the performance of the final design depends strongly on the initial design. Traditionally, the topology of the initial design is in most cases either chosen intuitively or inspired by already existing designs. However, there is a significant necessity of and interests in improving the quality of products by finding their best feasible topology in a very early stage of the design process. Topology optimization is an efficient tool for achieving this goal [8,9,10].

In this study, the discrete topology optimization method is integrated with the genetic algorithms for the determination of the optimal configuration of sliders with a specified taper and recess depth. The design objective is to minimize the variation of the flying height from the target value and the roll angel in the steady state. To compare the optimization result, we obtain the optimal configuration of a *H*-shaped slider. The new slider created via topology optimization shows better flying performance than the optimized *H*-shaped slider.

Optimization Procedure

Figure 1 shows the flow chart of the optimization procedure. The procedure consists of three modules. First, a cost function is chosen according to the specified design objectives and constraints. Then, the air-bearing surface is discretized and a one-to-one correspondence is generated between each discrete air-bearing surface and a binary string. Finally, a genetic algorithm is employed to find the optimal configuration of the slider that mini-

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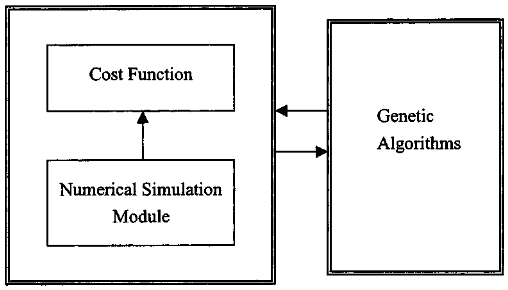

Fig. 1 Flow chart of the optimization procedure

mizes the cost function. Since the cost function should be calculated once for each possible design, it is essential to have a numerical algorithm that can efficiently determine the flying attitude for each design. Each module is described in detail below.

Formulation of the Optimization Problem

Variation in flying height results in a less efficient recording than would result with a uniform flying height. Also, an increased roll angle reduces the air-bearing stiffness and makes the flying height more sensitive to both static and dynamic effects [11]. For enhanced air-bearing characteristics, the slider is desired to maintain a uniform flying height and a small roll angle over the entire recording band [1]. In order to meet these requirements, the cost function is defined as

$$|H_{\min}-H^{*}|+R_{\max}+\alpha\cdot\sigma_H+\beta\cdot\sigma_R, \qquad (1)$$

where $H_{\min}$ and $R_{\max}$ indicate, respectively, the minimum flying height and maximum roll angle over the radius of the disk, H^{*} is the target flying height, σ_H and σ_R denote the standard deviations of the flying height and roll angle over the radius of the disk, α and β are the corresponding weighting factors, respectively.

The multi-criteria optimization problem is formulated as finding an air-bearing surface that minimizes the cost function (Eq. (1)) and satisfies the constraint

$$R\geqslant 0,$$

where R indicates the roll angle.

Discretization of the Air-Bearing Surface

The initial air-bearing surface design is composed of a flat surface and a front taper as shown in Fig. 2(*a*). The front taper serves to pressurize the air lubricant and thus provides the lift force. The admissible design domain is a rectangular parallelepiped with cavity depth δ, as indicated by the shaded region. In order to construct a negative pressure slider, some material in the admissible design domain should be removed. A rectangular uniform mesh is used to discretize the entire admissible design domain. The optimization consists in determining whether the material contained in each element should be removed or not. If the material contained in an element is removed, a rectangular cavity with recess depth δ is generated at the location of the element. In order to describe the shape of the slider, a variable of value 0 or 1 is assigned to each element. The value 0 indicates that the material contained in the element is removed. On the other hand, the value 1 represents a solid element. By doing this, we generate a one-to-one mapping between the slider geometry and a binary string. For example, the flat area shown in Fig. 2(*b*) is discretized by a 8×8 mesh. In this case, the slider configuration is described uniquely by a 64-bit binary string. The following binary string:

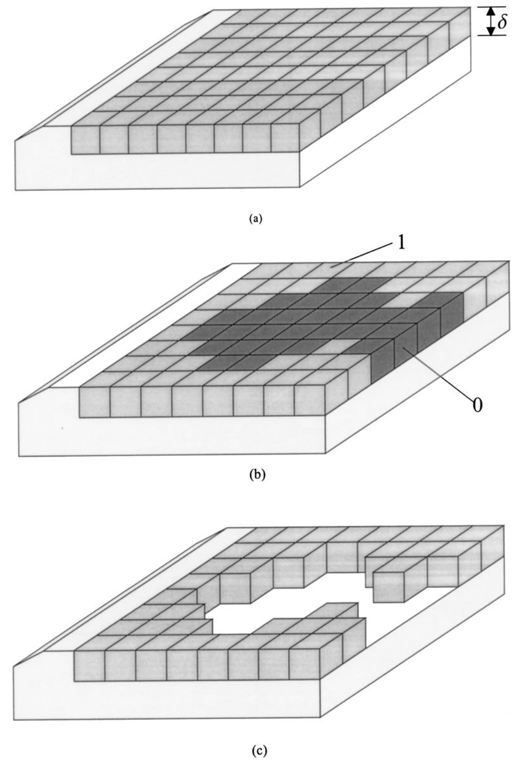

Fig. 2 Schematic of the grid-slider

1111111111100111110000111000000100000011100001111100111111000011

represents the slider configuration shown in Fig. 2(*c*). When discretizing the design domain, an even number of elements is preferred in both the cross and longitudinal directions. An odd number of elements in the cross direction can't represent ABS that is anti-symmetric with respect to the center line since all elements in the center are symmetric. Similarly, an odd number of elements in the longitudinal direction will limit the design space. In this work, an even number of elements are used in both the cross and longitudinal directions.

An l-bit binary string can represent a total of 2^l possible slider configurations. Then a genetic algorithm is used to find the optimal design among these possible configurations. In the remaining part of this paper, sliders generated in this way will be referred to as "grid-sliders."

Genetic Algorithms

Genetic algorithms are guided random search techniques simulating natural evolution. A genetic algorithm consists of a group of binary strings, where the bits of each string are considered the genes of an individual chromosome and where the group of individual chromosomes is said to be a population. Each binary string represents a feasible solution. The population is evolved with the use of the principles of variation, selection, and inheritance. There

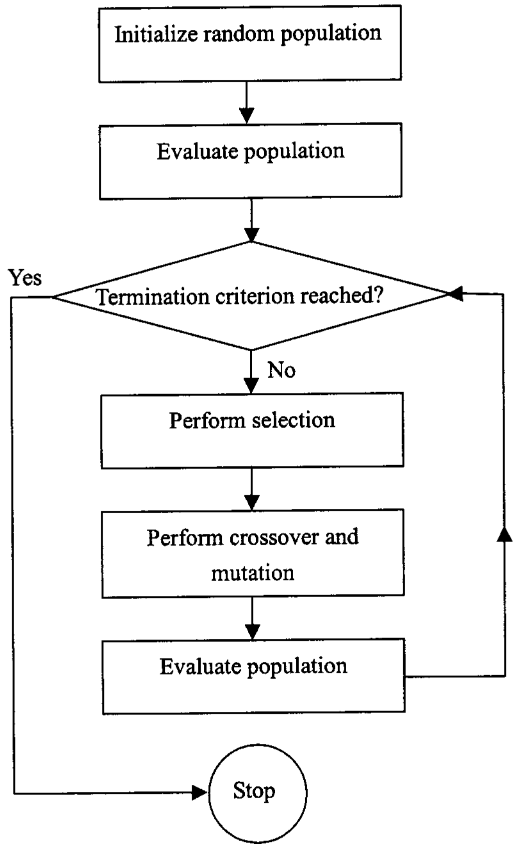

Fig. 3 Flow chart of the genetic algorithm

are many implementations of genetic algorithms [12]. The current implementation of the genetic algorithm is graphically depicted by Fig. 3 and described briefly below.

The initial population, consisting of n binary strings of length l, is generated randomly. Each string represents a possible design of the slider as shown in the previous section. The corresponding cost function of the slider is determined in the numerical simulation module and provides the mechanism for evaluating each individual. The linear scaling procedure described in [12] is used to determine the fitness value.

Once all individuals in the population have been evaluated, a new population of strings is formed in two steps. First, strings in the current population are selected for replication based on their fitness values. Replicating strings according to their fitness values means that strings with a higher fitness value have a higher probability of contributing one or more offspring in the next generation. By doing this, low-fitness individuals may be eliminated from the population. There are several ways for implementing the selection process. In this study, the proportional selection scheme is employed. In the proportional scheme, individuals are replicated in direct proportion to their fitness values. Next, genetic operators such as mutation and crossover are applied probabilistically to the selected individuals to produce a new population of individuals. Crossover is the combination of two strings to form two new strings, and mutation alters one or more bits of a selected string to introduce a new search direction. The resulting offspring are then inserted back into the population replacing older members to form a new generation of population. The optimality of the new generation is then evaluated and the process is repeated until some predetermined stop criterion is met.

Not all grid sliders generated randomly can fly under the specified suspension preload. For example, a chessboard-like slider with the binary representation as "10101010 . . . " may not fly. It is unlikely that genetic algorithms can generate good results in a reasonable amount of time if most of the ABS samples of the initial population can't fly. To avoid this situation, the initial population is generated in such a way that all of its ABS samples can fly. In the subsequent generations, a very small fitness value is assigned to the ABS sample that can't fly so that it won't be replicated in the next generation.

Numerical Simulation Procedure

The steady-state air-bearing pressure is governed by the generalized Reynolds equation as shown below

$$\frac{\partial}{\partial X}\left(QPH^3\frac{\partial P}{\partial X}-\Lambda_x PH\right)+\frac{\partial}{\partial Y}\left(QPH^3\frac{\partial P}{\partial Y}-\Lambda_y PH\right)=0, \quad (2)$$

where $P=p/p_a$ is the dimensionless pressure, $H=h/h_m$ the dimensionless bearing height, $X=x/L$ the dimensionless x-coordinate, $Y=y/L$ the dimensionless y-coordinate, in which p_a, h_m, and L indicate the ambient pressure, the flying height, and the length of the slider, respectively. $\Lambda_x=6\mu UL/p_a h_m^2$ and $\Lambda_y=6\mu VL/p_a h_m^2$ are the bearing numbers in the x and y directions, respectively, in which U and V are the x and y velocity components, respectively. Q is the flow factor that assumes different forms depending on the type of correction model used [13].

Patankar's [14] control volume method is employed to discretize the generalized Reynolds equation. The resulting nonlinear discrete equations are solved using an adaptive multigrid method [15]. In that method, an adaptive grid-generating scheme is implanted to discretize the computation domain such that fine grids are used only where needed. The final grid system consists of a sequence of uniform grids (or levels) with decreasing meshsizes. The Full Approximation Storage (FAS) algorithm, which suits well for solving nonlinear equations, is used to obtain solutions on these levels of grids [16]. The relative truncation error, a by-product of the FAS algorithm, is used in grid adaptation criteria. Finer meshes are only constructed over nodes of the current finest grid where the relative truncation error is over a predetermined tolerance. The domain of any grid may be only a proper part of the domains of the coarse grids underneath. Therefore, the total number of nodes of the adaptive multigrid method may be several orders less than that of a traditionally multigrid method. Since the computation work increases quickly with the node number, the adaptive multigrid method is much efficient than the traditionally multigrid method. It is well known that suitably fine meshes are needed around step discontinuities of the air-bearing surface for obtaining an accurate pressure profile. This makes the adaptive multigrid method especially powerful for the calculation of the pressure distribution for the grid sliders.

The numerical scheme described above is intended to solve the generalized Reynolds equation for the pressure distribution under the slider given the flying attitude, which consists of flying height, pitch and roll angle of the slider. However, in practice, the equilibrium flying attitude is desired given the suspension preload and the location of the load. This is called the inverse problem. Due to the nonlinearity of the generalized Reynolds equation, the inverse problem can only be solved through iteration. The solution starts at a guessed slider attitude. The pressure distribution under the slider is determined by the adaptive multigrid method. The magnitude and location of the resultant force of the pressure distribution are compared with those of the given suspension preload. If the difference is greater than the predetermined tolerance, the quasi-Newton iteration method [17,18] is employed to search for the new slider attitude. This process is repeated until the force equilibrium of the slider is reached.

Results and Discussion

We use a 30 percent negative pressure slider to demonstrate the effectiveness of the proposed topology optimization method. Figure 4 shows the geometric dimensions of the 30 percent slider. The recess depth is 3 μm. The inside and outside radii of the

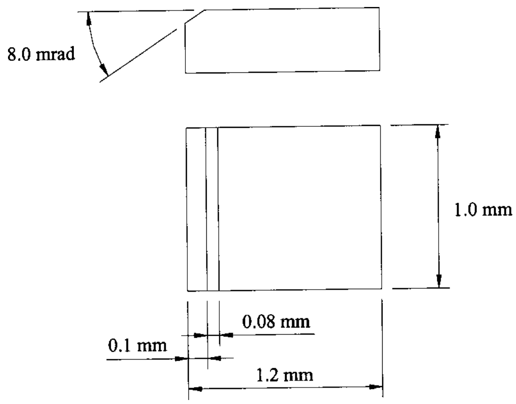

Fig. 4 Geometric dimensions of the 30 percent slider

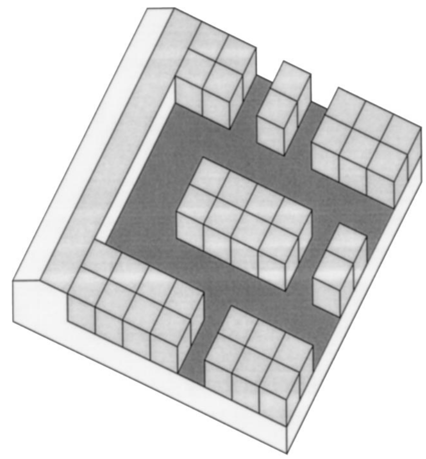

Fig. 6 Configuration of the optimal grid-slider

recording band are 24 and 40 mm, respectively, and the corresponding skew angles are 6.9 deg and 16.9 deg, respectively. The disk rotating speed is 5400 rpm and the suspension preload is 19.6 mN. The weighting factors in the cost function as defined by Eq. (1) are set as $\alpha = 10$ and $\beta = 5$, respectively. In this study, the cost function of each design is calculated at three points, located at the inner, center and outer radius of the disk.

Figure 5 shows the cost function value versus the generation, where the solid and dashed lines indicate the best solution and the average of the 50% best GA solutions, respectively. The population size is 15. As can be seen from the figure, the cost function value converges in 9 generations. The cost function value of the best design in the 9th generation is about one third of that in the first generation. The optimum configuration of the air-bearing surface and the corresponding pressure distribution at the center radius of the disk are shown in Figs. 6 and 7, respectively.

To compare the optimum grid-slider, we obtain the optimum configuration of a *H*-shaped slider. Figure 8 shows the schematic of the *H*-shaped slider and the design variables as indicated by X_1 to X_6. The recess depth and the taper of the *H*-shaped slider are the same as those of the grid-slider, respectively. The variations in flying heights and roll angles over the recording band of the optimum grid-slider (solid line) and *H*-shaped slider (dashed line) are plotted in Figs. 9(*a*) and 9(*b*), respectively. As can be seen from the figure, the optimal grid-slider has a nearly constant flying height. On the other hand, the flying height of the optimal *H*-shaped slider varies significantly over the recording band. Moreover, the optimal *H*-shaped slider has a cost function value of 86, which is larger than that of the optimal grid-slider. Therefore, we conclude that the optimum grid-slider is a better design than the optimum *H*-shaped slider.

For a slider of *n* elements and *m* height levels, the total number of possible designs is given by m^n. The grid-slider used to test the proposed optimization method has 80 elements and 2 height levels. Even for such a coarse grid size, the total number of possible designs, 2^{10}, is still so large that it is impractical to examine all the possible designs for finding the global optimal design. Because only a small fraction of the design space can be examined, it is unreasonable to expect an algorithm to locate the global optimum in the space. A more reasonable goal is to search for good regions of the design space corresponding to regularities in the problem domain. In the example shown above for optimizing the grid-slider, the total number of possible designs examined is $15 \times 9 = 135$. Although the number of designs examined is very

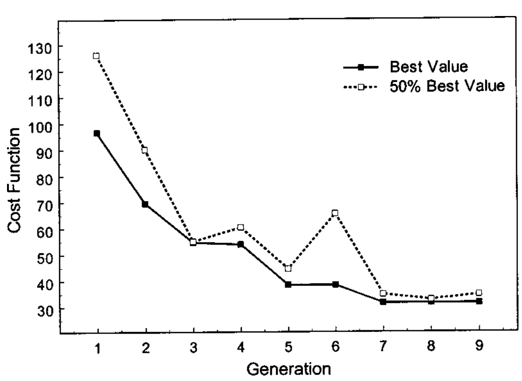

Fig. 5 Convergence history of the cost function for the grid-slider

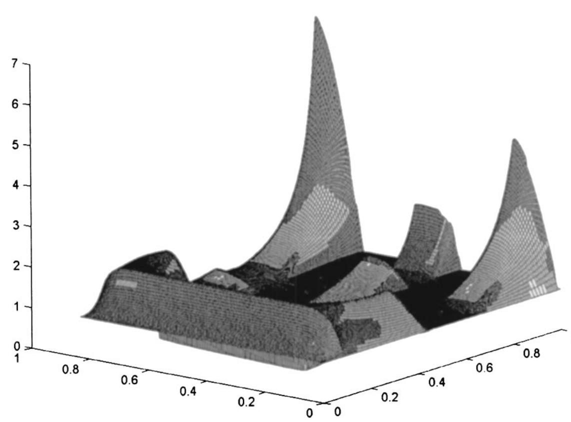

Fig. 7 Pressure distribution of the optimal grid-slider

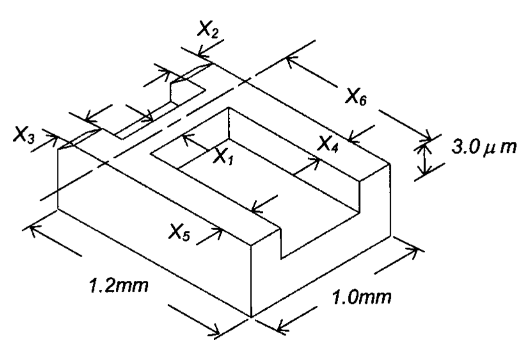

Fig. 8 Schematic of the *H*-shaped slider and the design variables

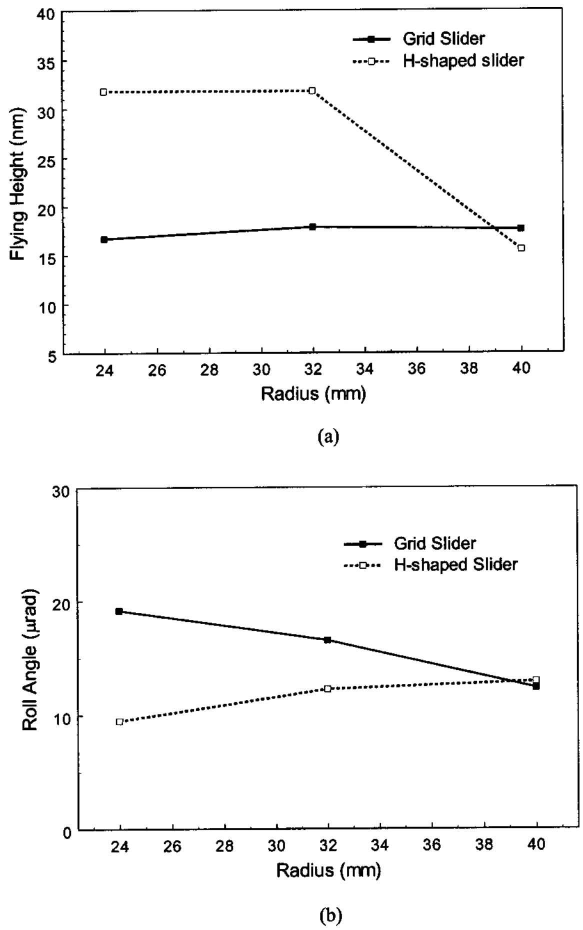

Fig. 9 Variations in the flying height (*a*) and roll angle (*b*) of the optimal grid-slider (solid) and *H*-shaped slider (dashed)

small compared with the total number of possible designs, the value of the cost function is reduced by a factor of three after the optimization process. In addition, the resulting optimal grid-slider shows a better flying behavior than the optimal *H*-shaped slider. This example shows that the proposed method has the ability for generating good designs efficiently.

Because only a fraction of the design space is searched, the genetic algorithms may yield some local optimum. In this case, the resulting design depends on the initial population and the parameters used, e.g., crossover rate and mutation rate. Moreover, since the crossover point and mutation bit are chosen probabilistically, different results may be generated even though the same initial population is used. Figure 10 shows a different optimized design using the same initial population as of Fig. 6. The cost value of the slider in Fig. 10 is 28, which is slightly less than that of the slider in Fig. 6. It may be advisable to run the optimization process several times with different sets of initial population and pick up the best result.

Complicated ABS may be required for meeting extremely performance demands. In this case, it is necessary to employ a large grid size for describing the ABS properly. Since the total number of possible designs increase with the grid size exponentially, it is reasonable to employ a large population size for finding the optimal design when the grid size is large. In addition, a fine computational mesh is required for determining the pressure distribution under the ABS when solving the corresponding inverse problem. These two factors make the computer time increase dramatically with the grid size. Whether it is practically possible to use a large grid size depends on if the optimization process can be finished in a reasonable amount of time. One possible way to reduce the computation time is to employ the parallel computation power of modern computers. Another possible approach is to combine the present method with the ''subregion'' method proposed by Hanke and Talke [10]. The subregion method is similar in principle to the present method. Both methods employ the discrete topology optimization approach for generating novel ABS designs. In the subregion method, the design area is discretized into a number of small rectangular subregions. All the possible designs are examined to find the global minimum at the first step. After determining an optimum solution with an initial coarse subdivision, a refinement of the solution is obtained by further subdivision of the individual subregions, and repeating the process to determine the optimum solution. When the subregion or the grid size is large, it is impractical to examine all the possible designs for determining the optimum solution. Due to this restriction, the design area used in the subregion method is only a fraction of the entire ABS. The previous grid-slider example shows that genetic algorithms are capable of generating good results when only a fraction of the design space is searched. Therefore, by using the genetic algorithms for finding optimal solutions, the design area can be extended to cover a larger portion of the ABS and the whole optimization process can still be finished in a reasonable amount of time. A combination of the present method with the subregion method is currently under investigation.

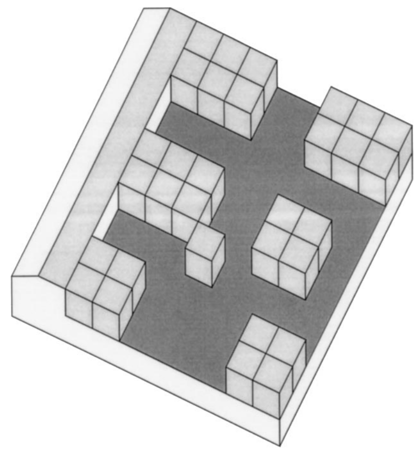

Fig. 10 A different optimal grid-slider using the same initial population as of Fig. 6

In the present method, the design area is subdivided into a number of rectangular elements. Therefore, it is not suitable for modeling complicated ABS whose sidewalls are not perpendicular. The use of nonrectangular elements or unstructured grid is seemingly a fruitful topic for future research.

Conclusions

This study presents a topology optimization method for developing designs of sliders for computer hard disk drives. The present method does not require a priory knowledge of a good initial design and generates novel designs of ABS. A 30 percent taper slider is used to demonstrate the effectiveness of this method. The cost function is the summation of the steady state minimum flying height, the absolute value of the maximum roll angle, and the variations in the flying height and roll angle over the entire recording band. First, a uniform mesh of suitable size is generated to divide the air-bearing surface into rectangular elements. Each element is assigned a value of either one or zero. If the value is zero, the material in the element is removed and a cavity of a specified recess depth is generated. If the value is one, the element is unchanged. In this way, the air-bearing surface configuration can be characterized by a binary string. Then, the simple genetic algorithm is used to find the optimum solution from the possible candidates. The slider created via the topology optimization method shows better flying performance than a *H*-shaped slider optimally designed by a traditional optimization method.

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