Head Slider Designs Using Approximation Methods

Sang-Joon Yoon, Dong-Hoon Choi*
Center of Innovative Design Optimization Technology, Hanyang University, Seoul 133-791, Korea

This paper presents an approach to optimally design the air bearing surface (ABS) of the head slider by using the approximation methods. The reduced basis concept is used to reduce the number of design variables. In the numerical calculation, the progressive quadratic response surface modeling (PQRSM) is used to handle the non-smooth and discontinuous cost function. A multi-criteria optimization problem is formulated to enhance the flying performances over the entire recording band during the steady state and track seek operations. The optimal solutions of the sliders, whose target flying heights are 12 nm and 9 nm, are automatically obtained. The flying heights during the steady state operation become closer to the target values and the flying height variations during the track seek operation are smaller than those for the initial one. The pitch and roll angles are also kept within suitable ranges over the recording band.

Key Words : Head Slider, Approximation Method, Optimun Design

1. Introduction

Although the conventional optimizations of ABS shapes have been studied (Yoon and Choi, 1995 ; O'Hara and Bogy, 1995), they usually demand long computing time in proportion to the number of design variables. For that reason, Choi et al.(1999) simplified the shape of ABS to be symmetric around the centerline of the slider, and chose only a few configuration parameters dominantly affecting the flying performance as the design variables. However, this approach could not handle asymmetrical ABS shapes, and also depended on the designer's skill to select the proper variables.

For applications of nonlinear programming methods to large design problems, many of approximation concepts have been proposed (Barthelemy and Haftka, 1993). To approximate a design problem is one possible way to reduce the number of design variables effectively. The reduced basis concept, one of the global problem approximation methods, was originally suggested by Picket et al.(1973). Vanderplaats (1979) selected the existing good designs of airfoil as the basis shapes instead of the trial designs, and found the improved shapes by superposing them. Yoon et al.(2002) selected the commercial designs of head slider as the basis shapes, and then obtained the optimum designs from them.

In the optimum design involving a large number of design variables, some feasible design vectors may be available to start with. Since these design vectors may have been suggested by experienced designers, the size of the optimization problem can be reduced by expressing the design vector as a linear combination of the available feasible design vectors. When the reduced basis concept is employed, the cost functions with respect to the combination coefficients are not ensured to be smooth and continuous any more. Therefore, a function-based approximation algorithm instead of the conventional gradient-based optimization algorithm is employed.

In this study, we perform the design optimiza-

* Corresponding Author,
E-mail : dhchoi@hanyang.ac.kr
TEL : +82-2-2290-0443; **FAX** : +82-2-2291-4070
Center of Innovative Design Optimization Technology, Hanyang University, Seoul 133-791, Korea. (Manuscript **Received** September 5, 2002; **Revised** October 9, 2003)

tion in order to obtain the improved flying performance during the track seek operation as well as the steady state operation. The ABS shapes with respect to two target flying heights are optimally designed, and they show better flying performance than the conventional slider.

2. Optimum Design Problem

Introducing the reduced basis concept, the design variable vector $\mathbf{x}$ can be replaced with the combination of the basis shapes as

$$\mathbf{x}=\mathbf{x}^c+\sum_{k=1}^{n} q_k\mathbf{x}^k \qquad (1)$$

where $\mathbf{x}^c$ is a constant vector added for generality and $\mathbf{x}^k$ is a basis shape vector. q_k is a combination or participation coefficient. If the j_{th} element of ith basis shape vector is x_j^i, then the j_{th} design variable composed by the combination of n basis shapes is defined as

$$x_j=x_j^c+q_1x_j^1+q_2x_j^2+\cdots+q_nx_j^n \qquad (2)$$

The recent pico slider, whose target flying height h^* is less than 15 nm, tends to have a stiction problem. This problem can be solved by adding studs to the ABS, which reduces the contact area. To prevent the contact between the pads and disk over the recording band, the higher pitch angle and the strictly confined roll angle are required. Since the changes in flying height and roll angle during the track seek operation have a large impact on the drive reliability, they should also be restricted. Therefore, the design requirements regarding the optimization of slider bearings are defined as follows:

- The flying height variation from target value should be minimized during the steady state and track seek operations.
- The pitch angle should be kept within a suitable range during the steady state operation.
- The roll angle should be minimized within a suitable range in order to prevent the slider from contacting the disk surface during the steady state and track seek operations.

In this study, the recess depth δ_1 and the shallow step depth δ_2 of the slider as well as the combination coefficients q_i mentioned above are chosen as the design variables since they have a major influence on the flying attitude parameters.

This problem is a multi-objective optimization since it is a parametric problem to handle the variations of flying attitude parameters with respect to the radial positions over the recording band. A common approach to the multi-objective optimization is to minimize the sum of the individual objective functions, using a weighting factor to indicate the importance of each objective. However, since the variation of flying height h, pitch angle α, and roll angle β as a function of the radial position are known to be smooth and continuous over the recording band, we concentrate on the smallest and/or the largest values of these flying attitude parameters. Both weighting factors are also set to 1. Denoting the smallest and largest values by the subscripts min and max, respectively, we can formulate a multi-criteria optimization problem as follows: find the design variables

to minimize

$$F=\{(h_{\min}/h^*-1)^2+(h_{\max}/h^*-1)^2\} \qquad (3)$$

satisfying

$$\alpha^L\le\alpha\le\alpha^U \qquad (4)$$

$$\beta^L\le\beta\le\beta^U \qquad (5)$$

$$h^*-\gamma_h\le h^{OD}\le h^*+\gamma_h \qquad (6)$$

$$h^*-\gamma_h\le h^{ID}\le h^*+\gamma_h \qquad (7)$$

$$\beta^L\le\beta^{OD}\le\beta^U \qquad (8)$$

$$\beta^L\le\beta^{ID}\le\beta^U \qquad (9)$$

$$\delta^L\le\delta_{1,2}\le\delta^U \qquad (10)$$

$$q^L\le q_i\le q^U,\ \sum_{i=1}^{n} q_i=1\,(i=1,2,\cdots,n) \qquad (11)$$

Here, n is the number of basis models. The superscripts L and U denote lower and upper limit values respectively, and the superscripts OD and ID signify the track seek values. OD means to move the slider from inner track to outer track in the radial direction and ID means that the slider comes back from outer track to inner track. h^* denotes the target value for the flying height and γ_h is the positive value for the tolerance of the flying height.

The cost function of Eq. (3) represents the maximum variation of the normalized flying height according to the radial positions. The constraints of Eqs. (4) and (5) are the ranges of the pitch angle and roll angle, respectively. Equations (6) ~ (9) are the maximum deviations from the target values of the flying height and the ranges of the roll angle during the track seek operation. The side constraints of Eqs. (10) and (11) are imposed to bound the values of design variables explicitly within practical ranges.

The cost and constraint functions with respect to the combination coefficients are not smooth and continuous any more due to the combination of basis shapes. Hence, we employ the PQRSM (Hong et al., 2001) as a function-based approximation algorithm instead of the conventional gradient-based optimization algorithm using the gradient information. This method approximates cost and constraint functions by the quadratic function within the reasonable design space, and then solves the approximate optimization problem. However, this method is more effective than the other approximation methods because it does not require the additional computing time to explicitly construct an approximate model. If the number of design variables is n, for example, this method requires only $2n+1$ design points for one approximate optimization.

The overall procedure for solving the optimization problem of Eqs. (3) ~ (11) is as follows. The initial values of design variables are assumed, which define the ABS shape of the initial model slider. Given the slider configuration, the flying attitude parameters in steady state are calculated at seven equally spaced radial positions. And then, the flying attitude parameters during the track seek operation are also calculated at seven evaluation points in the similar manner. Here, the number of evaluation points is increased from five to seven due to the nonlinearity on the gain/loss of air-bearing skew angle and air-flow velocity during the track seek operation as shown in Fig. 1.

For the numerical simulation of the track seek operation, the quasi-static approach is used because the track seek motion can be described by

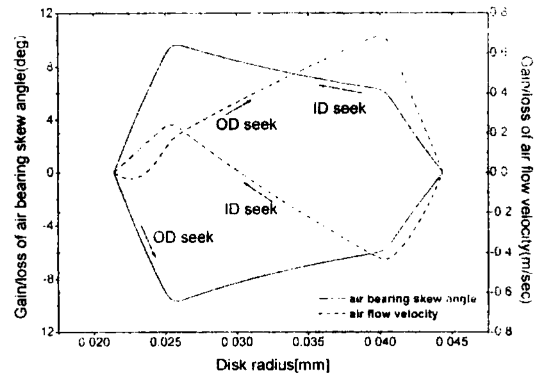


Fig. 1 Gain/loss of air-bearing skew angle and air-flow velocity during track seek

the changes of the air-bearing skew angle and air-flow velocity (Cha et al., 1995). The corresponding cost and constraint values are obtained by using these values. In the current design, these cost and constraint values are updated by using the nonlinear programming technique. This whole process is repeated until the convergence criteria are satisfied (Choi et al., 1999).

3. Computational Results

To evaluate the effectiveness of the design methodology suggested in this study, a computer program is developed based on the numerical procedure described in the previous section, and then applied to the configuration design of slider air bearings with respect to two target flying heights.

The inside and outside radii of the recording band are specified as 21.41 and 44.37 mm, respectively, and the corresponding skew angles as -6.18 and $+16.69$ deg, respectively. When the slider leaves for outer track from inner track, it is accelerated to 2.5 m/s until 25.41 mm, followed by constant velocity to 40.37 mm, and then decelerated to 0 m/s at outer track. The slider then comes back toward inner track following the same profile. Figure 1 shows the gain/loss of the air-bearing skew angle and air-flow velocity during the full stroke track seek operation.

The commercialized slider with five rails and four shallow steps shown in Fig. 2(a) is chosen as a basis model, which is defined as pico form-factor (30% or 1.235×1.0 mm). Each of rails has the crown of 24 nm and the camber of 8.2 nm. The preload is 3 gf, which is applied at the center of the slider by a suspension. The static pitch angle is 1 degree and the disk rotating speed is 5400 rpm.

Four commercially available slider models are selected as the basis shape as shown in Fig. 2(b). Here, the region of trailing rails is not included in basis vectors as modification vectors since the central trailing rail including the magnetic head is restricted to change and also the left-right trailing rail is not installed in all basis models. Hence, $\mathbf{x}^c$ in (10) is set by positions of trailing rails of the last model. The basis vectors are also defined, in which the entries corresponding to positions on trailing rails are zero. Since the 4th basis shape is used as an initial slider model, as the initial values of the design variables, δ_1^0 and δ_2^0 are 1.524 μm and 0.1524 μm and $\boldsymbol{q}^0$ is $\{0\ 0\ 0\ 1\}^T$.

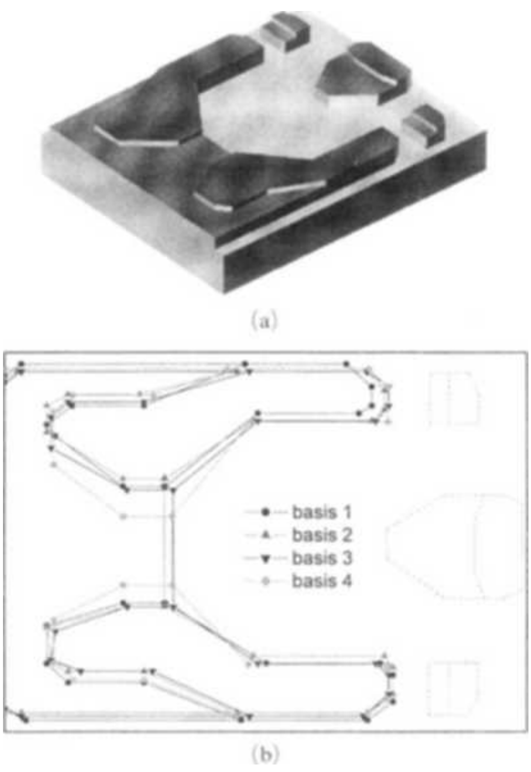


Fig. 2 Basis shapes of the model sliders

q_4 becomes a dependent variable from Eq. (11).

The flying height is estimated at the trailing edge where the magnetic head is located. The lower and upper limits for pitch angle are 170 μrad and 250 μrad, respectively, and for roll angle -4 μrad and 4 μrad, respectively. γ_h is set to be 1 nm. The lower and upper limits for the combination coefficients are -1 and 1, respectively, where its negative value makes the feasible design space resulting from the combination efficiently increase. In this study, two target flying heights of 12 nm and 9 nm are assigned to illustrate the automatic configuration design feature of our approach.

The original and optimum values of the design variables are presented in Table 1. Figure 3 also shows their geometries with respect to two target sliders, respectively. Both of them are much alike

Table 1 Normalized optimum results

Design variable	Lower	Initial	Optimum 12 nm	Optimum 9 nm	Upper
$\delta_1[\mu m]$	0	1	1.109	0.990	2
	(0)	(1.524)	(1.690)	(1.509)	(3.048)
$\delta_2[\mu m]$	0	1	0.805	0.629	2
	(0)	(0.1524)	(0.1227)	(0.0959)	(0.3048)
q_1	−1	0	0.819	0.590	1
q_2	−1	0	−0.254	−0.248	1
q_3	−1	0	−0.487	−0.343	1

*( ) denotes its dimensional value.

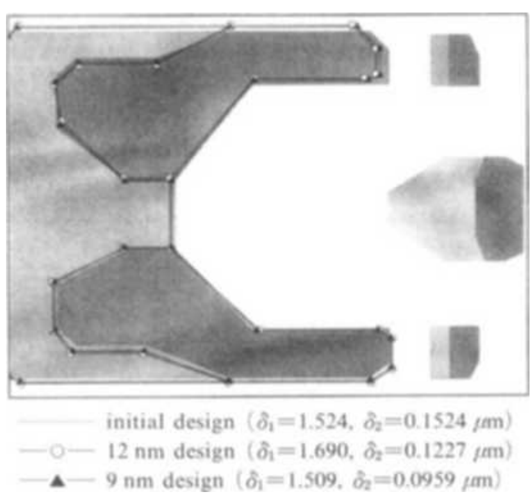


Fig. 3 Initial and optimized designs

in overall geometries except recess and shallow step depths. It is demonstrated that the variation of the asymmetric shape in the ABS leads to an enhancement of flying performances. And, the changes of the recess and shallow step depths are dominant in handling the target flying height.

For the 12 nm target, the optimization has increased the recess depth by 11 percent from 1.524 μm for initial design to 1.690 μm for the optimum one, while decreasing the shallow step depth by 19 percent from 0.1524 μm to 0.1227 μm. The 9 nm target has reduced the recess depth by 1 percent from 1.524 μm to 1.509 μm, while decreasing the shallow step depth by 37 percent from 0.1524 μm to 0.0959 μm. As a result, the changes of the recess and shallow step depths are dominant to handle the target flying height, and the variation of the asymmetry leads to an enhancement of flight performance.

The convergence history of the cost value for each target model shows good convergence to the optimum solutions as shown in Fig. 4(a) and 5 (a). For the 12 nm target, the numbers of the iteration is 5 and that of the cost function evaluations is 89. The constraint values also represent no constraint violation at the optimum solution as shown in Fig. 4(b). For the 9 nm target, it is shown that the numbers of the iteration and the cost function evaluations are 5 and 56, respectively. The constraint values also represent no constraint violation at the optimum solution.

In order to compare the flying characteristics of the optimum design with those of the initial ones, we plot the variation of flying height, pitch angle,

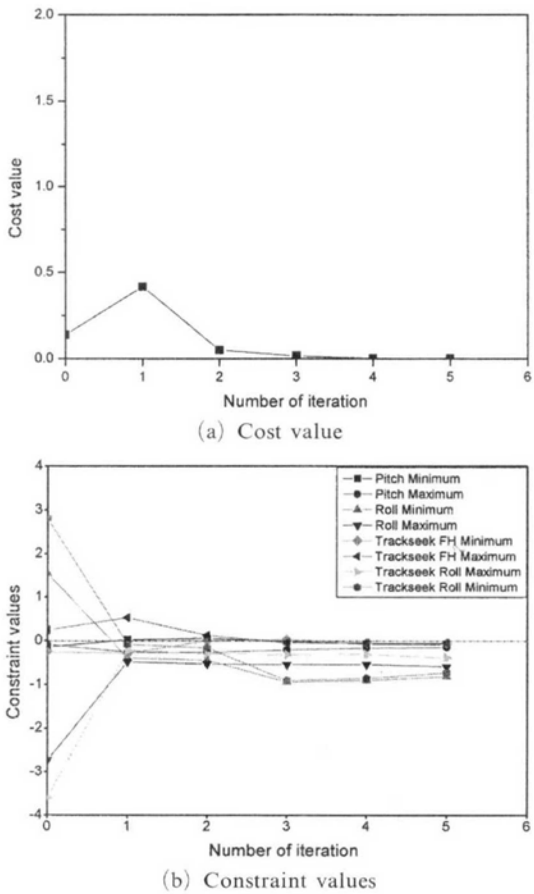


Fig. 4 Convergence history of the cost and constraint values for 12 nm target

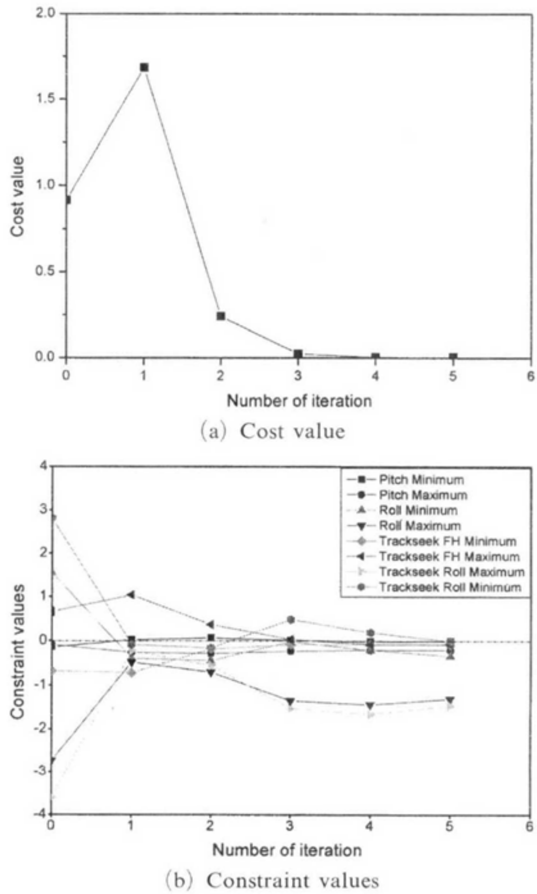
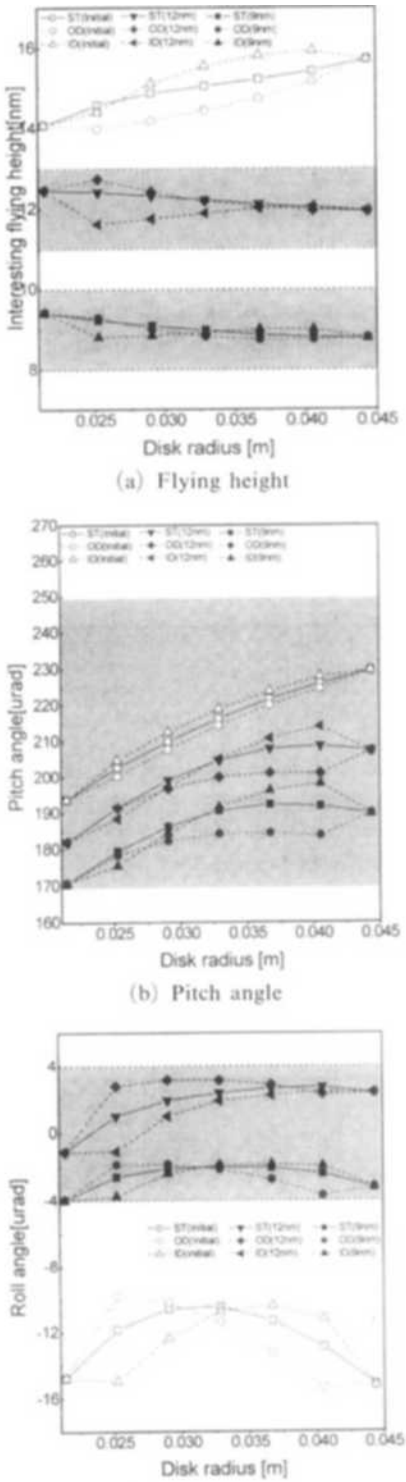


Fig. 5 Convergence history of the cost and constraint values for 9 nm target

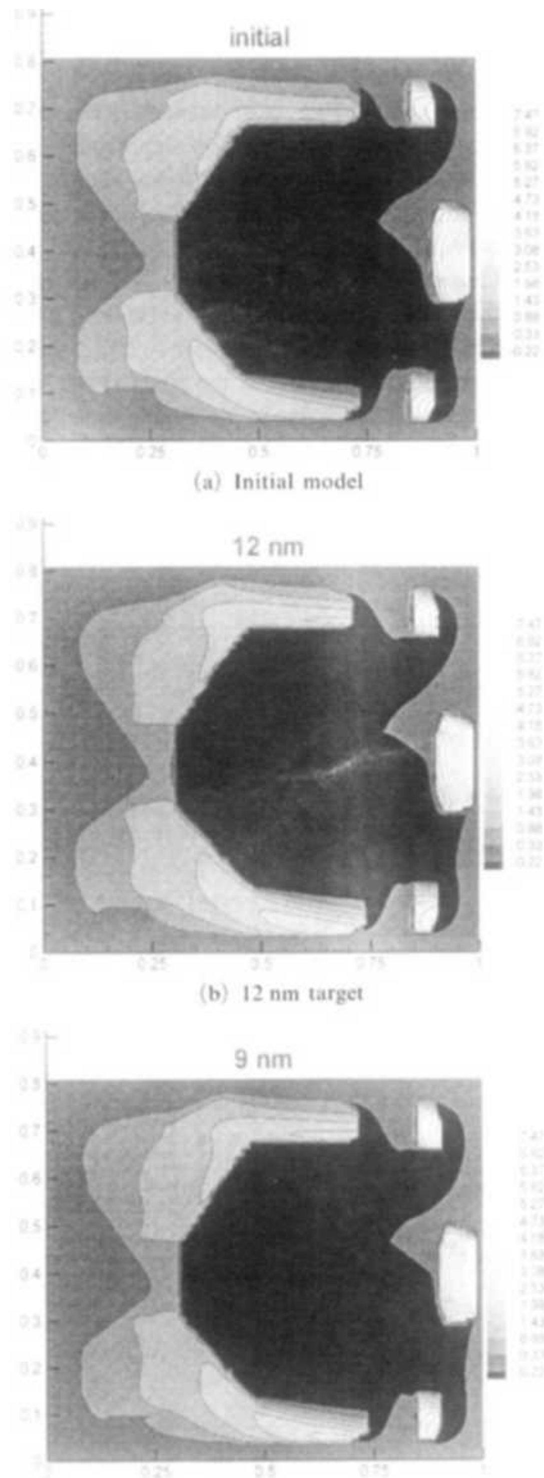


(a) Flying height

(b) Pitch angle

(c) Roll angle

Fig. 6 Flying characteristics of the initial and optimum designs



(a) Initial model

(b) 12 nm target

(c) 9 nm target

Fig. 7 Pressure distribution of initial and optimized sliders and roll angle along the disk radius in Fig. 6(a), (b), and (c), respectively. The flying heights during the steady state (ST) and the track seek operations (OD and ID) are shown in Fig. 6(a). The result of the 12 nm target shows that the largest deviation from the target flying height is reduced by 50 percent from 0.92 nm to 0.46 nm in the steady state operation in addition to satisfying the constraints of flying height during the track seek operation. The result of the 9 nm target also shows the reduction of 54 percent from 0.92 nm to 0.42 nm. Figure 6(b) shows that the pitch angles of the optimum designs satisfy the constraints. As shown in Fig. 6(c), the roll angles of the optimum designs satisfy the constraints during the steady state and track seek operations, whereas the initial one violates all of them.

To investigate the effects of the optimized ABS shapes, Fig. 7 shows the pressure distributions at outer diameter of the disk. Here, the brightness of the shading refers to the magnitude of the pressure under the ABS. The significant change in geometry is the increase of the front pressure area of inside rail in addition to the recess depth area shown as the dark black color. On the other hand, the front pressure area of outside rail decreases in order to keep the balance of asymmetric rail.

The conventional optimization approach may need more than 60 design variables to determine the configuration of the ABS due to the number of x-y spatial coordinates of vertices, while the proposed approach can obtain the optimum design with only 5 design variables. As a result, it implies that the optimum solution with the reduced basis concept is less than one-tenth of that with the conventional methods in the amount of calculation.

4. Conclusions

In this study, we proposed the configuration designs of an asymmetric slider, where the entire ABS should be handled as a design domain, by using the approximation methods. The reduced basis concept was introduced to effectively reduce the number of design variables. As a function-based approximation algorithm, PQRSM was applied to handle the non-smooth and discontinuous functions in the optimization process as well as to save the required computing time.

A multi-criteria optimization problem was formulated to enhance the flying performances over the entire recording band during the steady state and track seek operations. The numerical procedure was then established to automatically find the optimum values of the design variables. Our program was applied to the two target flying heights of 12 nm and 9 nm with four commercial basis models.

The optimum configurations of the target sliders were successfully obtained while both of them met all design requirements mentioned in the previous section. It was demonstrated that our approach is efficient since optimum designs can be found by only drastically reduced computing effort in spite of covering the entire design domain of the ABS as design variables.

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