KSTLE International Journal, Vol. 5, No. 1, June 2004, pp. 23-27

On Application of Optimization Scheme To Direct Numerical Analysis Of Slider

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Abstract: The object of the present work is the numerical analysis of the computer hard disk slider. The pressure between slider and disk surfaces is calculated using the Boundary Fitted Coordinate System and Divergence Formulation for the nonlinear Reynolds' equation solution. The optimization scheme is applied to search for the steady state position of the slider. The simplified method is given for the case of the fixed inclined pad. The film thickness ratios and pitching and rolling angles are considered as alternative choice of the slider's coordinates. The behavior of the objective function for the Negative Pressure slider is studied in details. Methods of conjugate directions and feasible directions are applied.

Key words: Steady state position, gas lubrication, optimization, hard disk drive slider

Introduction

The main computer data storage, such as the hard disk drive has several heads (sliders) and disks. The heads are used to read and write the magnetic records on the disk. The shape of the slider surface and the slider's position provide generation of high pressure in the air film between the rotating disk and the slider. Further increase of the hard disk capacity is desired in modern computer applications. The increasing of the data storage density defines requirements to new slider design. The slider's size and shape must provide ultra low flying height (about several nanometers) in steady state position, low sensitivity to alteration of external pressure, disk surface velocity, skew angle and external excitations.

Sliders, which have cavities where the subambient pressure is generated, are called Negative Pressure Slider. The suction force pulls such a slider close to the disk surface [1]. Other advantages of the NPS are high stiffness, fast take-off and low sensitivity to external pressure. More complicated shapes of NPS are required to satisfy other conditions, such as constant flying height for different skew angles between disk velocity and slider axes [2]. Zeng and Bogy [3] have developed the design of a slider with high damping, which suppresses unwanted vertical head oscillations.

The solution of the nonlinear Reynolds' equation, which describes the pressure distribution in the air film, is essential part of the numerical analysis of the slider. This time-consuming procedure must be done many times to determine the steady state position of the slider and it's dynamic behavior. Fukui and Kaneko [4] prepared the database that can be used to decrease the time of the pressure calculation.

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The Reynolds equation can be solved using different discretization methods, such as Finite Difference Method, Finite Element Method [5] or Divergence Formulation [6], which is also called Direct Numerical Method. FEM has some advantages for example a wide choice of possible mesh elements. Wu and Bogy [7] developed the method of the triangular mesh adaptation that improves the pressure calculation. The DF enables modeling of the step-like slider surface. Kawabata [6] applied the Boundary Fitted Coordinate System to DF method to deal with complicated slider shapes.

Many researchers investigated static behavior of sliders, described by its' load carrying capacity, flying height and pitch angle [1,8]. Also significant improvement of the sliders flying characteristics was achieved by using dynamic analysis, which means evaluation of air bearing stiffness and damping coefficient in slider position near the steady state [2,3,9]. But hitherto no special attention was drawn to improvement of the steady state search methods. In the present work the optimization scheme is applied to the slider's steady state position search in order to decrease the required number of the pressure calculations.

General problem statement

The distribution of pressure in the air film between the slider and the disk is described by the nonlinear Reynolds equation, dimensionless form of which is

$$\frac{\partial}{\partial X}\left(H^3 P\frac{\partial P}{\partial X}\right) + \alpha^2\frac{\partial}{\partial Y}\left(H^3 P\frac{\partial P}{\partial Y}\right) = \Lambda_X\frac{\partial}{\partial X}(HP) + \Lambda_Y\frac{\partial}{\partial Y}(HP) \tag{1}$$

where $H(X,Y)$ is dimensionless air film thickness, $P(X,Y)$ is dimensionless pressure, Λ_x and Λ_y are compressibility numbers

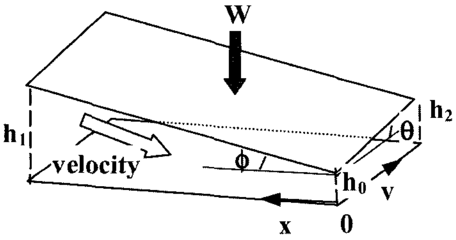

Fig. 1. The position of the slider (h_0 = minimal film thickness, W = slider weight, ϕ = pitch angle, θ = roll angle).

$$\Lambda_x = \frac{6U\eta b}{h_0^2 p_0}, \quad \Lambda_Y = \frac{6V\eta b^2}{h_0^2 p_0 l} \tag{2}$$

And α is slider length to width ratio

$$\alpha = l/b \tag{3}$$

Term with time derivative of H, which expresses the air film damping, is absent in Eq. (1), because the static problem is considered.

The position of slider above the disk is shown on the Fig. 1. When the minimal film thickness h_0 is chosen as a unit of height, then the distribution of the dimensionless film thickness can be written as

$$H(X, Y) = \frac{h_s}{h_0} + 1 + \phi\frac{Xb}{h_0} + \theta\frac{Yl}{h_0} \tag{3}$$

where $h_s(X,Y)$ is determined by the slider surface shape.

So, for the given shape of slider the pressure distribution $p(x,y)$ depends on slider position (h_0, ϕ , θ).

The load carrying capacity is defined as follows:

$$L = \iint p(x, y)dxdy \tag{4}$$

It produce the rotational moments about the slider pivoting point (xp, yp)

$$\begin{aligned} M_{L\phi} &= \iint p(x, y)(x - x_p)dxdy \\ M_{L\theta} &= \iint p(x, y)(y - y_p)dxdy \end{aligned} \tag{5}$$

The weight of slider W acts through the slider's mass center (x_c, y_c).

So the total force in vertical direction

$$F = L - W \tag{6}$$

And total moments about the pivoting point are

$$\begin{aligned} M_\phi &= M_{L\phi} + W(x_c - x_p) \\ M_\theta &= M_{L\theta} + W(y_c - y_p) \end{aligned} \tag{7}$$

The condition of the steady state is

$$\begin{aligned} F &= 0 \\ M_\phi &= 0 \\ M_\theta &= 0 \end{aligned} \tag{8}$$

To represent the steady state position search as an optimization problem, the total objective function is defined as

$$f = f(h_0, \phi, \theta) = \left(\frac{F}{L_0}\right)^2 + \left(\frac{M_\phi}{M_{\phi 0}}\right)^2 + \left(\frac{M_\theta}{M_{\theta 0}}\right)^2 \tag{9}$$

where $L_0 = W$, $M_{\phi 0} = 0.1Wb$ and $M_{\theta 0} = 0.1Wl$ are units of force and moments. The minimum of such function f is equal zero and corresponds to steady state search, the level $f = 0.1$ corresponds to the steady state search accuracy 10%, the level $f = 1$ corresponds to 100% accuracy and so on.

The alternative sliders coordinate set is (h_0, kx, ky), where

$$\begin{aligned} k_x &= \frac{h_1 - h_0}{h_0} = \frac{\phi b}{h_0} \\ k_Y &= \frac{h_2 - h_0}{h_0} = \frac{\theta l}{h_0} \end{aligned} \tag{10}$$

express the film thickness ratio in x and y directions. The coordinate set (h_0, k_x, k_y) has advantage over the coordinate set (h_0, ϕ, θ), because the dimensionless film thickness depends on minimal film thickness only where $h_S \neq 0$.

$$H(X, Y) = \frac{h_s}{h_0} + 1 + k_X X + k_Y Y \tag{11}$$

From other points of view these two coordinate sets are equivalent, so choose the second one.

Thus the problem is

$$\begin{aligned} &\text{Minimize } f(h_0, k_x, k_y) \\ &\qquad h_0 > 0 \\ &\text{subject to } k_x > 0 \\ &\qquad k_y > 0 \end{aligned} \tag{12}$$

The Alternative Problem Statement for the Approximation of the Flat Slider and Thick Air Film

For the flat slider, such as $h_S(X,Y) = 0$, calculations of F, M_ϕ and M_θ have shown, that they are monotonic functions of h_0, k_x and k_y (Fig. 2).

This result is with good agreement with analytical solution for fixed-incline slider bearing [10].

In this case the objective function f defined by Eq. (9) has only one local minimum, corresponding to global minimum, where $f = 0$. So the steady state position can be found, using any local optimization technique, considering constraints given by (12) and starting from any initial position.

For thick air film, corresponding to compressibility numbers $\Lambda_x \approx 1$, $\Lambda_Y \approx 1$, Eq. (1) can be approximated to linear form [10]

$$\frac{\partial}{\partial X}\left(H^3\frac{\partial P}{\partial X}\right) + \alpha^2\frac{\partial}{\partial Y}\left(H^3\frac{\partial P}{\partial Y}\right) = \Lambda_x\frac{\partial H}{\partial X} + \Lambda_Y\frac{\partial H}{\partial Y} \tag{13}$$

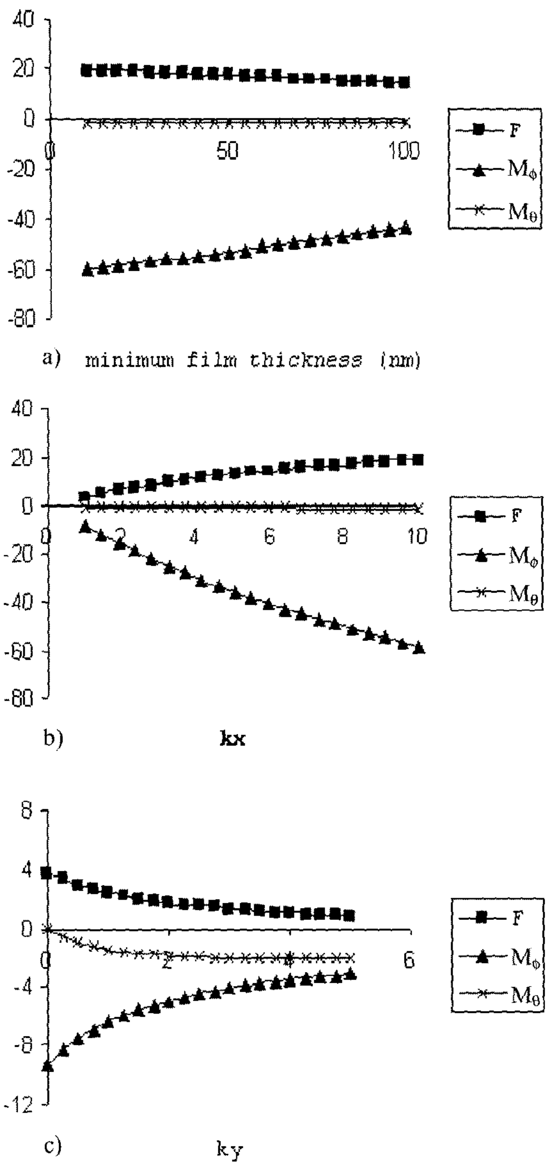

Fig. 2. The load carrying capacity and moments of the flat slider (a) versus minimal film thickness h_0, (b) versus film thickness ration in x-direction kx and (c) versus film thickness ration in y-direction k_y.

For the flat slider $H(X,Y)$ does not depend on h_0. Hence Eq. (13) has the solution in form

$$P(X, Y) = \Lambda_X(h_0) \cdot g(X, Y) \quad (14)$$

where $\Lambda_X(X,Y)$ is defined by (2) and $g(X,Y)$ does not depend on h_0, but on k_x and k_y only. Then air film load carrying capacity and load moments also can be written as

$$L = \Lambda_X(h_0) \cdot g_1(k_x, k_y)$$
$$M_{L\phi} = \Lambda_X(h_0) \cdot g_2(k_x, k_y) \quad (15)$$
$$M_{L\theta} = \Lambda_X(h_0) \cdot g_3(k_x, k_y)$$

The coordinates of the air film pressure center

$$x_L = M_{L\phi}/L = g_2/g_1$$
$$y_L = M_{L\theta}/L = g_3/g_1 \quad (14)$$

in the case of mass center and pivot point coincidence can be used for alternative formulation of the steady state search problem.

Minimize $G(k_X, k_Y) = (x_L - x_P)^2 + (y_L - y_P)^2$

Subject to $k_x > 0$ (15)
$k_y > 0$

And after this for given k_x and k_y
Find zero of $F(h_0)$
Subject to $h_0 > 0$ (16)

For the same optimization methods the summarized difficulty of the problems (15) and (16) is less than the one of the problem (12). So for the slider with an almost flat surface, flying on a thick air film this approach is useful.

General problem solution

As was mentioned above the main requirement to the modern slider design is the ultra low flying height. It means that usually the approximation of the thick air film cannot be applied and the compressibility number is very big, more than 1000.

The surface of the most of sliders is not flat, it has some steps and cavities, designed to change pressure distribution so, that the flying characteristics of the slider will be improved.

Because of these reasons it is impossible to split the general three-dimensional problem (12) into a sequence of optimization problems with a lower dimension that would be universal for all practical types of sliders. So the general problem solution requires minimization of the total objective function f, such as defined by Eq. (9) in three dimensional space of slider's position coordinates (h_0, ϕ, θ) or (h_0, k_x, k_y).

Then for the search of the steady state position of slider based on the NPS it is important to use the moments M_ϕ, M_θ, not the load center coordinates x_L, y_L. At some slider location the load carrying capacity of the NPS can vanish, and the load center coordinates, as a function of the slider position, will have discontinuity.

Several models of the NPS were considered in order to determine the general behavior of the objective function. One of the results is given on the Fig. 3. The main conclusion of this investigation: the objective function can have several local minima, but the global minimum coincides with the steady state position.

Hence there are two possible ways to solve this problem. The first one is to choose some global optimization scheme, such as the Genetic Algorithm of the Simulated Annealing. The second one is to use some local optimization scheme with very strict constraints, so that in this slider position range there is the only one local minimum, which corresponds to the steady state position. The first way seems to provide better

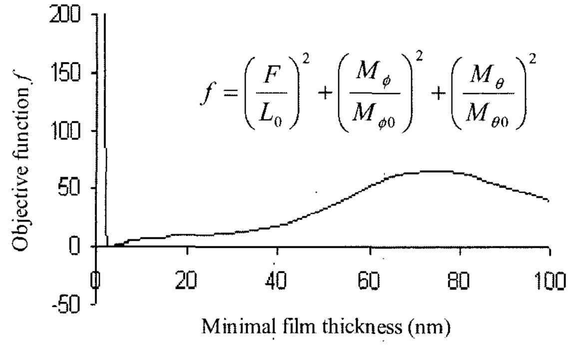

Fig. 3. The example of objective function in a wide range of minimal film thickness for NPS.

automation of the steady state search, since the second one requires manual search of the appropriate slider position range.

But actually the second one is more preferable, due to next reasons. First, the estimation of the steady state position is quite easy, when several similar sliders are analyzed consequently. Second, the convergence of the pressure calculation tends to be poor for conditions, significantly different from the steady state.

The feasible directions method of constrained optimization [11] is chosen to unclose the search trajectory in a given range of h_0, k_x and k_y.

The considered objective function behaves as the quadratic function in vicinity of the minimum. So the methods, based on use of the conjugate directions might be a good choice.

The derivatives $\frac{\partial f}{\partial h_0}, \frac{\partial f}{\partial k_X}, \frac{\partial f}{\partial k_Y}$ can be calculated as follows:

$$\frac{\partial f}{\partial h_0} \approx \frac{\Delta f}{\Delta h_0}, \frac{\partial f}{\partial k_X} \approx \frac{\Delta f}{\Delta k_X}, \frac{\partial f}{\partial k_Y} \approx \frac{\Delta f}{\Delta k_Y} \quad (17)$$

where Δf is calculated from $\Delta p(x,y)$ - the small disturbance of pressure distribution corresponding to small disturbance of the air film $\Delta H(X,Y)$. The equation on $\Delta p(x,y)$ is the linearized form of Eq.(1). The linearity provides fast calculation of $\Delta p(x,y)$ in comparison to calculation of $p(x,y)$. So the conjugate direction optimization using derivatives will be the reasonable choice.

Conclusions

The optimization problem statement, equivalent to the steady state search problem is presented.

The fast solution is derived for sliders, which can be approximated as flat thick film sliders.

For more advanced designs of sliders, based on the NPS, the necessity of multidimensional search in three dimensions is proved.

It was found that in the general case the local minimum of the objective function is not unique, but from the practical point of view it is better to use local minimization subject to restricted constraints.

The combination of the feasible directions method with the conjugate direction method with using derivatives is found to be the best choice for this problem.

Nomenclature

b	= the slider's length
F	= the total force, applied to slider in vertical direction
f	= the objective function
G	= the alternative objective function
H	= dimensionless air film thickness; $h/h0$
h	= the air film thickness
h_0	= minimal film thickness, the flying height
h_S	= the slider's shape function, the difference in position of the real slider surface and the flat surface
k_x, k_y	= the air film thickness ratio; $(h_1-h_0)/h_0$ and $(h_2-h_0)/h_0$
L	= the air film load carrying capacity
l	= the slider's width
M_ϕ, M_θ	= the total moments in pitch and roll directions about the slider's mass center
$M_{L\phi}$, $M_{L\theta}$	= the moments of the air film force
P	= dimensionless pressure; p/p_0
p	= the air film pressure
p_0	= external pressure
U, V	= the disk surface velocity in x and y direction
X,Y	= dimensionless coordinates; x/b and y/l
x_c, y_c	= coordinates of the slider's mass center
x_L, y_L	= coordinates of the pressure center
x_P, y_P	= coordinates of the pivoting point
α	= the length to width ratio; b/l
Δ	= the small disturbance of some quantity
Λ_x, Λ_y	= the compressibility numbers; $\frac{6U\eta b}{h_0^2 p_0}$ and $\frac{6V\eta b^2}{h_0^2 p_0 l}$
ϕ	= the slider's pitch angle
θ	= the slider's rolling angle

Acknowledgments

Authors would like to appreciate the financial support provided for continuing this research by Brain Korea 21 project in 2003.

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