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Modeling and Simulation of the Interaction Between Lubricant Droplets on the Slider Surface and Air Flow Within the Head/Disk Interface of Disk Drives

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The dynamic interaction phenomenon between three-dimensional (3-D) lubricant droplets located on the air bearing surface and air flow within the head-disk interface is modeled and numerically simulated. A strong interaction is observed for ultra low flying slider design. The droplet motion and deformation are able to induce non-negligible air bearing force and moment change, which in turn may impose a non-negligible disturbance on the slider's flying attitude.

Index Terms—Air bearing, disk drives, head/disk interface, interaction, lubricant flow.

I. INTRODUCTION

IT IS estimated that the flying height of air bearing sliders has to be reduced to about 3.5 nm to further increase the areal storage density of disk drive to 1 Tbits/in². At such a small clearance, which is approaching the thickness of the lubricant layer coated on the disk surface (about 1.5 nm), the interaction between the air flow and lubricant flow may become non-negligible and has to be considered in the designing of next generation head/disk interface technology. Previous researches have demonstrated that the air flow and lubricant flow under the slider are coupled together and the interaction imposes a non-negligible impact on the flyability of low-flying sliders [1]–[5]. In addition, the industry also needs a model that can quantitatively predict the distribution of lubricant contaminations on the slider surface.

Our previous simulations based on a simplified two-dimensional (2-D) model show that a lubricant droplet introduced onto the slider surface may interact strongly with the air flow and trigger significant air bearing force and moment change for low flying sliders [6]. In this paper, we extend the 2-D model to a three-dimensional (3-D) model. A new governing equation is derived for the lubricant flow on the air bearing surface, which includes important physics such as viscous force, air bearing pressure, air shearing force, surface tension and disjoining pressure. Again, a very strong coupling between the lubricant droplet motion and air flow is discovered for ultra low flying slider design. The lubricant droplet is driven to migrate towards the slider's trailing edge predominantly by the air shearing stress. Other effects such as air bearing pressure gradient and disjoining pressure gradient play a secondary role. The droplet simultaneously undergoes significant shape deformation. The moving and deforming droplet in turn modifies the effective air bearing surface profile and induces a corresponding air flow adjustment. Our results based on the new 3-D droplet model show that the lubricant droplet and air flow interaction may induce a non-negligible air bearing force, pitch moment

Fig. 1. Diagram of head/disk interface setup.

and slider's flying attitude change for low-flying slider design. Our model is also able to quantitatively predict lubricant contamination distribution on the slider surface.

II. GOVERNING EQUATIONS AND NUMERICAL METHODS

A. Lubricant Film Thickness Evolution Equation

Under lubrication condition, the mass balance equation for the lubricant flow is

$$\frac{\partial h_l}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (1)$$

where t is time, x and y are the horizontal coordinates, and h_l is the lubricant film thickness (see Fig. 1). The volume flow rates of lubricant per unit length in x and y directions are

$$\begin{aligned} q_x &= \int_0^{h_l} u dz = -\frac{1}{3\mu_l} \frac{\partial p_l}{\partial x} h_l^3 + \frac{\tau_x}{2\mu_l} h_l^2, \\ q_y &= \int_0^{h_l} v dz = -\frac{1}{3\mu_l} \frac{\partial p_l}{\partial y} h_l^3 + \frac{\tau_y}{2\mu_l} h_l^2 \end{aligned} \quad (2)$$

where u and v are lubricant velocities in x and y directions, μ_l is the lubricant viscosity, τ_x and τ_y are the air shearing stresses in x and y directions, respectively. The pressure within the lubricant film can be obtained through a normal stress balance at the interface to yield

$$p_l = p_a - \frac{A}{h_l^3} - \sigma \left[\frac{\partial^2 (h_l + h_s)}{\partial x^2} + \frac{\partial^2 (h_l + h_s)}{\partial y^2} \right] \quad (3)$$

where p_a is the air bearing pressure, A is the modified Hamaker constant, σ is the surface tension of lubricant and h_s is the vertical elevation of the air bearing surface from the fully recessed cavity region, respectively. The meniscus curvature induced capillary pressure term in (3) has two contributions: One directly comes from the change of film thickness $h_l(x, y)$, the other from the air bearing surface topography change $h_s(x, y)$. Substituting (2) and (3) into (1) and normalizing it, we obtain the dimensionless evolution equation for the lubricant droplet profile

$$\begin{aligned} \frac{\partial(H_l)}{\partial T} + \frac{\partial}{\partial X} \left[\tau_x^* H_l^2 - C_p \frac{\partial P}{\partial X} H_l^3 - C_d \frac{1}{H_l} \frac{\partial H_l}{\partial X} \right] \\ + C_\sigma H_l^3 \frac{\partial^3 (H_l + H_s)}{\partial X^3} \\ + \frac{\partial}{\partial Y} \left[\tau_y^* H_l^2 - C_p \frac{\partial P}{\partial Y} H_l^3 - C_d \frac{1}{H_l} \frac{\partial H_l}{\partial Y} \right] \\ + C_\sigma H_l^3 \frac{\partial^3 (H_l + H_s)}{\partial Y^3} = 0 \quad (4) \end{aligned}$$

where $T = 2t\mu_l L/(\mu_a U)$, $X = x/L$, $Y = y/L$, $H_l = h_l/h_f$, $H_s = h_s/h_f$, $P = p_a/p_0$, and $\tau_x^* = \tau_x h_f/(\mu_a U)$, $\tau_y^* = \tau_y h_f/(\mu_a U)$ are the dimensionless time, tangential coordinates, lubricant thickness, height of air bearing surface, air bearing pressure and air shearing stresses in the x and y directions, respectively. The disk's linear velocity in x direction, slider's length, flying height, air viscosity and ambient air pressure are denoted U , L , h_f , μ_a and p_0 , respectively. The dimensionless groups $C_p = 2p_0 h_f^2/(3\mu_a L U)$, $C_d = 2A/(\mu_a L U h_f)$ and $C_\sigma = 2\sigma h_f^3/(\mu_a L^3 U)$ represent the ratios of air bearing pressure, disjoining pressure and capillary pressure to the air shearing stress, respectively.

The material parameters for the perfluoropolyalkylether (PFPE) lubricant are: $\mu_l = 0.1448 \text{ Pa}\cdot\text{s}$, $\sigma = 0.02 \text{ N/m}$ and $A = 10^{-21} \text{ J}$. For a typical slider design flying at a 10 nm height ($L \sim 1 \text{ mm}$, $U \sim 10 \text{ m/s}$), the order of magnitudes of the dimensionless parameters in (4) are: $C_p \propto 10^{-5}$, $C_d \propto 10^{-5}$, and $C_\sigma \propto 10^{-13}$.

The extremely small values of C_p , C_d and C_σ from dimensional analysis show that the air bearing pressure, disjoining pressure and capillary pressure have a much smaller effect on driving the lubricant flow compared with the air shearing stress. The air pressure and disjoining pressure terms are included in our simulations. The capillary pressure terms are ignored in the following simulation.

B. Numerical Methods

At each moment, the steady state modified Reynolds equation is solved by a finite volume method using the known lubricant droplet profile. Because the viscosity of air is several orders smaller than that of the lubricant, it is reasonable to assume that the air flow adjusts itself instantly in response to the lubricant droplet profile change. The resulting air bearing pressure is employed to calculate the air shearing stresses from the first-order slip model velocity profiles [6]. Equation (4) is then numerically solved by an implicit hybrid finite difference method [7]. The time marching continues until a targeted time is reached.

III. RESULTS AND DISCUSSION

In the following discussion, we assume that the initial shape of each lubricant droplet is described by a spherical cap. We

Fig. 2. Geometry of a modified IBM Travelstar slider design. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 3. Initial dimensionless profile of droplets on the slider surface. The droplets have a height of 60 nm. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 4. Contour of lubricant distribution on the slider surface after a sliding of 800 s. (Color version available online at <http://ieeexplore.ieee.org>.)

use a modified IBM Travelstar slider to illustrate the interaction mechanism (see Fig. 2). The slider is flied at a fixed attitude ($h_f = 3.5 \text{ nm}$, pitch = $100 \mu\text{rad}$, roll = 0). Three droplets are

Fig. 5. Skin friction lines of air shearing stress on the slider surface. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 6. Contour of a lubricant droplet after 10 s sliding. The droplet is initially located (1.1, 0.5 mm) with a height of 10 nm and a radius 0.1 mm. (Color version available online at <http://ieeexplore.ieee.org>.)

initially placed near the leading edge of the slider (see Fig. 3). Fig. 4 shows that the droplets are removed quickly from the air bearing surface by the strong air shearing and are driven into the fully recess cavity region. In the cavity region, the droplets meet to form a lubricant ridge circumscribing the trailing pad and the majority of lubricant is drained toward the two spots on the trailing edge along the two branches of the ridge. The ridge is separated from the trailing pad at the leading edge and its two branches gradually converge to the side walls of the trailing pad. Fig. 5 plots the skin friction lines of the air shearing stress at the slider surface. Figs. 4 and 5 show that the lubricant evolution pattern on the slider surface is predominantly driven by the air shearing stress pattern. The lubricant ridge is formed at places where skin friction lines converge. Fig. 5 also indicates the existence of a reverse air flow region in front of the trailing pad close to the slider surface, which is induced by the pressure gradient there. Our simulation shows a few percent change in the air bearing force during the simulated time period.

Fig. 6 plots the contour of a droplet after a sliding duration of 10 s. The droplet is introduced at the trailing pad before sliding. The majority of lubricant flows to the trailing edge

Fig. 7. Air bearing force evolution as a function of the initial droplet height.

quickly driven by the strong air shearing at the pad surface. Fig. 7 plots the evolution history of the air bearing force. Fig. 7 shows that the air bearing force initially increases with time and reaches a maximum value. Then it decreases and approaches the air bearing force without any lubricant on the pad surface. The interaction strength increases with the size of the droplet. Fig. 7 shows that the interaction becomes stronger when droplets are introduced at the trailing pad than at other place.

IV. CONCLUSION

A new flow model is developed for the interaction phenomenon between droplets located on the air bearing surface and the air flow within the head disk interface of disk drives. Our simulation indicates that the interaction between the droplets motion and the air flow may become strong enough to induce non-negligible air bearing force and moments change when the lubricant droplets are driving to migrate towards the trailing edge of the slider. The interaction phenomenon has to be considered in the designing of next generation head/disk interface technology with an ultra low flying head. The new model is able to quantitatively predict lubricant contamination distribution on the slider surface.

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