Effects of Track-Seeking Motion on the Flying Attitudes of Ultralow Flying Sliders

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The flying height (FH) change during a track-seeking motion becomes of significant concern for ultralow flying sliders. The presence of nanoscale adhesion forces, such as intermolecular and electrostatic forces, can adversely decrease the FH and even cause head-disk impact. A quasi-static approximation of track-seeking motion is proposed here, which if sufficiently accurate can substantially decrease the computation time over that required for a dynamic analysis. The track-seeking performances of four different air bearing surface (ABS) designs are numerically investigated by the quasi-static approximation, and the results are compared with those computed by the CML Dynamic Simulator. The former gives good agreements with the latter but with much less computation effort. The effects of various factors causing FH changes are presented and compared quantitatively. The effective skew angle is found to be the dominant factor, but the inertia effect is also not negligible. Two designs, called Scorpion III and IV, designed previously as active FH control sliders, are found to exhibit an enhancement in track-seeking performance, compared with two other conventional ABS designs.

Index Terms—Flying height, hard disk drives, head-media interface, intermolecular and electrostatic forces, track-seeking motion.

I. INTRODUCTION

A FLYING height (FH) of less than 5 nm is required for ultrahigh density recording. For such ultralow flying sliders the changes in FH during track-seeking motions not only cause signal loss, but also significantly increase the risk of head-disk contact. Moreover, the presence of nanoscale adhesion forces, such as intermolecular and electrostatic forces, can cause dynamical instability. In order for a reliable head-disk interface to be maintained the FH change and contact between the slider and disk have to be avoided. Different air bearing surface (ABS) designs can perform quite differently during the track-seeking process. Therefore, the dynamic track-seeking performance of air bearing sliders is becoming of increasing importance. A better understanding of the factors that cause FH change should help improve the ABS design to achieve better track-seeking performance.

Cha *et al.* [1] studied the FH change during seek operation for transverse pressure contour (TPC) sliders. They suggested that at high seek velocities the skew angle effect dominates over the inertia effect but there was no quantitative comparison between the cases with and without inertia effects due to the difficulty of measuring FH during track-seeking and the absence of proper dynamic simulators. Liu and Soh [2] experimentally investigated the effects of track-seeking velocity on air bearing skew angle, air flow speed and flying performance of TPC and Tri-pad sliders. The effects of the slider's inertia and acceleration were not considered. Chen and Bogy [3] conducted a numerical study of the track-seeking dynamics of two different sliders using the CML Dynamic Simulator. They found that the two sliders had distinct dynamic characteristics. The Dynamic Simulator included the inertia effect and provided more comprehensive simulations of track-seeking dynamics but it required much more computation time.

In this paper, we propose a quasi-static approximation of the track-seeking motion, which includes the effects of slider inertia, effective skew angles and nanoscale adhesion forces in the head-disk interface (HDI). We first compare the track-seeking simulations of four ABS designs by quasi-static approximation with those obtained using the CML Dynamic Simulator on a smooth disk surface. Then we quantitatively study the effects of various factors on the FH change.

II. THEORETICAL BACKGROUND AND NUMERICAL METHODS

A. Air Bearing Slider and Suspension Dynamics

The equations of motion of an air bearing slider flying over a rotating disk are

$$m\ddot{z} = F + \int_A (p - p_a)dA$$
$$I_\theta\ddot{\theta} = M_\theta + \int_A (p - p_a)(x_g - x)dA$$
$$I_\phi\ddot{\phi} = M_\phi + \int_A (p - p_a)(y_g - y)dA \quad (1)$$

where z, θ, and ϕ are the vertical displacement, pitch, and roll, respectively. I_θ and I_ϕ are the moments of inertia, x_g and y_g are the positions of the slider's center of gravity, and F, M_θ and M_ϕ are the force and moments exerted on the slider by the suspension. For track-seeking motions, M_θ and M_ϕ include the contribution of the inertia forces. The pressure distribution p is calculated by solving the generalized Reynolds equation. p_a is the ambient pressure and A is the area of the ABS.

The CML Dynamic Simulator was developed to solve the generalized Reynolds equations coupled with the dynamics of the slider body and a lumped parameter suspension, where the suspension is represented by flexure stiffness and damping coefficients. By using the simulator, we can obtain the dynamic flying attitude of a slider during track-seeking motions. However, since the time step used in the dynamic simulation is usually on the order of 1×10^{-7} s, it requires considerable com-

putation effort to conduct one track-seeking simulation with an average seeking time of 11 ms.

B. Quasi-Static Approximation of Track-Seeking Motion

In order to reduce the computation effort of track-seeking simulations and quantitatively study the contribution of various factors on the FH change during track-seeking, we carried out a quasi-static approximation of the track-seeking motion. Instead of simultaneously solving the Reynolds equation and the equations of motion at each time step, we solve the Reynolds equation under static suspension loading with consideration of the seeking velocity and slider inertia at different radial positions during track-seeking. The change of seeking velocity causes changes of skew angle and air flow speed and direction. The geometrical skew angle refers to the angle between the slider's longitudinal axis and the track direction. The effective skew angle is the angle between the slider's longitudinal direction and the relative disk velocity which is the resultant vector of the disk track linear velocity and the slider's seeking velocity. As the seeking velocity increases, the difference between the geometrical and effective skew angles increases.

The acceleration of the center of gravity of a slider during track-seeking can be expressed as

$$a = a_t e_t + a_n e_n = a_t e_t + (\omega^2 r) e_n \qquad (2)$$

where a_t and a_n are the tangential and normal components, respectively. ω and r are the angular velocity of the arm and the arm length of the VCM actuator, respectively. The tangential component is also referred to as the seeking acceleration. Since the inertia effect of the suspension has minimal effect on the roll angle and FH, only the inertia of the slider is considered in this study. The additional torques exerted on the slider body due to these inertia forces can be written as

$$\Delta M_\theta = -m \cdot a_n \cdot \frac{h}{2} \qquad \Delta M_\phi = -m \cdot a_t \cdot \frac{h}{2} \qquad (3)$$

where m and h are the mass and thickness of the slider.

III. RESULTS AND DISCUSSIOKONS

A. Air Bearing Designs and Track-Seeking Performances

We study the track-seeking performances of four negative pressure ABS designs. The first design, depicted in Fig. 1(a), is a five-pad design labeled ABS I. It was designed using an optimization algorithm [4] for a nearly uniform 5-nm FH across the disk. The second and more complicated design is shown in Fig. 1(b) and labeled ABS II. The third and fourth designs, named Scorpion III and Scorpion IV, were designed as controlled-FH sliders with thermal and piezoelectric nanoactuators [5], [6], respectively. For a controlled-FH slider, the FH is about 10 nm in the off duty cycle and is reduced to ~2 nm during reading and writing by applying either a current or a voltage to an active element, such as a resistive heating element or piezoelectric material. As shown in Fig. 1(c) and (d), the areas of their central trailing pads have been significantly reduced to increase the actuation efficiency. The high pressures generated at the side rails of Scorpion III and IV support the sliders and help achieve high stiffness, especially in the roll direction. The increase of roll stiffness can effectively reduce variations of roll angle due to inertia forces. Therefore decreases in the minimum FH are
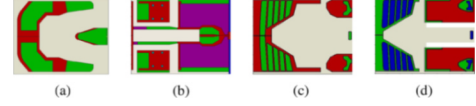

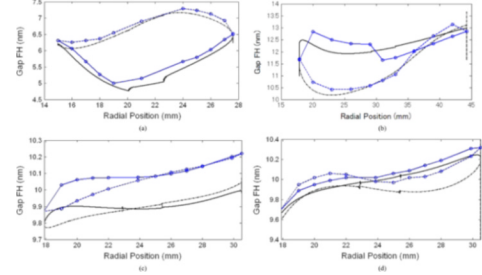Fig. 1. Four ABS designs used in this study. (a) ABS I. (b) ABS II. (c) Scorpion III. (d) Scorpion IV. (Color version available online at http://ieeexplore.ieee.org.)

Fig. 2. FH changes during track-seeking motion. The maximum seek acceleration is 637 m/s². (— Dynamic ID->OD, – – – – – Dynamic OD->ID, –o–Static ID->OD, –o–Static OD->ID). (a) ABS I. (b) ABS II. (c) Scorpion III. (d) Scorpion IV. (Color version available online at http://ieeexplore.ieee.org.)

held to a minimum. Also, these features help generate high pressure and large negative force, which are expected to reduce the sensitivity of the FH to the change of skew angle.

The maximum seeking acceleration is 637 m/s² for all of the four ABS designs and the other parameters, such as velocity, radial position, geometrical and effective skews are determined by the length of the VCM actuator and the distance between the pivot and the center of the disk according to specifications of each product. The simulation starts with an outward seek that is followed by an inward seek, thus completing a full-stroke seeking loop. For the outward seeking process of ABS I, the slider is first accelerated to 2.55 m/s in 4 ms, followed by 1 ms of constant velocity, then it is decelerated to zero velocity in 4 ms. During the seek the geometrical skew angle changes from −1.2 to 14.0 degrees. For the inward seek, we simply reverse the outward seeking process. Although the actual seeking profile in disk drives may be different, the major characteristics of track-seeking motion are contained in the profiles used in this study.

Fig. 2 illustrates comparisons of gap FHs during the corresponding full-stroke seeking loop between dynamic simulations and the quasi-static approximations. It is seen that for all the designs the quasi-static approximations demonstrate good agreements with the dynamic simulations. The inertia effect is clearly seen in the FH curves. The Scorpion III and IV sliders exhibit extremely small FH, pitch and roll variations, which can significantly reduce the risk of head-disk contact during track-seeking motion.

B. Factors Causing FH Change

To investigate the contributions of effective skew, inertia and air-flow speed to the FH change, we performed quasi-static simulations of the ABS I slider with different combinations of the various factors. Fig. 3(a) shows the minimum FH change when the slider moves from ID to OD. The curve labeled "Track-following" shows the FH without seeking. The curve labeled "with roll and pitch torques" includes the effects of tangential (roll torque) and normal acceleration (pitch torque), effective skew and air flow speed. This is used as a baseline for comparing the contributions of the factors. It is observed that the FH drops
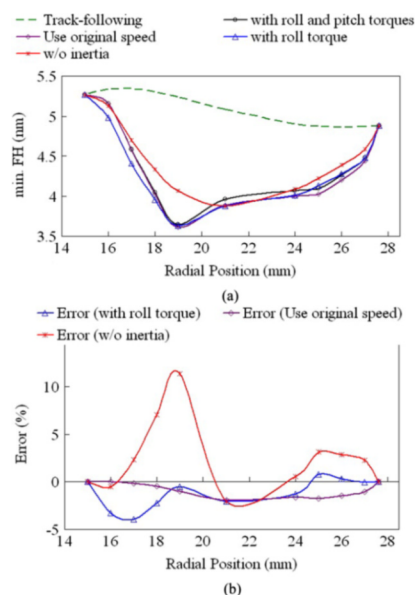
Fig. 3. Effects of the effective skew, inertia forces, and air flow speed on the FH changes of ABS I from ID to OD. (Color version available online at http://ieeexplore.ieee.org.)
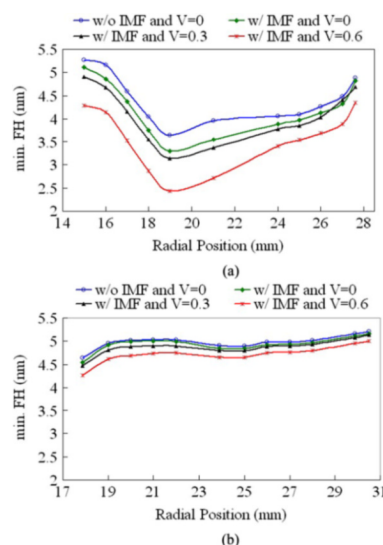

Fig. 4. FH drops caused by the adhesion forces. (IMF stands for the intermolecular force; V is the electrical potential across the HDI). (Color version available online at http://ieeexplore.ieee.org.)

about 1.5 nm near the MD. The effect of effective skew angle on the FH drop is the difference between the curve "Track-following" and the curve "w/o inertia." It is clearly seen that the skew angle change is the dominant factor that causes the FH change during track-seeking. The contributions of the other factors are shown in Fig. 3(b). The error is defined as the ratio of the FH difference to the baseline value. The result without the inertia effect has an error of 12% near the radial position of 19 mm, which is attributed to the roll angle change. The effect of centrifugal forces caused by normal acceleration has an error of less than 5% and the effect of the change of the air flow speed has an error of less than 2%.

In order to study the effect of intermolecular and electrostatic forces on the minimum FH during track-seeking motion we performed quasi-static simulations for ABS I and Scorpion IV with a 4-nm actuation stroke in the presence of these forces. The effect of intermolecular forces was included with a nominal value of the Hamaker constant $(A = 8.9 \times 10^{-20} \text{J})$ and the electrostatic forces were added with different electrical potentials $(V = 0, 0.3 \text{ and } 0.6 \text{ V})$ between the slider and the disk. The minimum FHs of ABS I and Scorpion IV are shown in Fig. 4(a) and (b), respectively. It is seen that the FH of ABS I drops over 30% near the radial position of 19 mm while Scorpion IV exhibits a much smaller and more uniform FH drop of less than 10 %. The improvement of the Scorpion ABSs on track-seeking motion is primarily due to their insensitivity to skew angle and their extremely high roll stiffnesses.

IV. CONCLUSION

This paper proposes a quasi-static approximation of the track-seeking motion, which includes the effects of head—gimbal assembly (HGA) inertia, effective skew angles and nanoscale adhesion forces in the HDI. The track-seeking simulations of four ABS designs by the quasi-static approximation give good agreements with those by the CML Dynamic Simulator but with much less computation time. A quantitative study of the effects of various factors on the minimum FH change during track-seeking shows that the effective skew angle is dominant but the inertia effect is not negligible. Intermolecular and electrostatic forces were found to add to the FH drop of ABS I during the track-seeking. However, even with an electrical potential of 0.6 V and intermolecular forces, the FH drop of Scorpion IV remains less than 10%. Even though the FH change and the adverse effect of these forces during track-seeking cannot be completely attenuated, a properly designed air bearing slider that decreases its sensitivity to skews, minimizes these forces and increases the roll stiffness can greatly enhance the track-seeking performance.

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