Controlled-Flying Proximity Sliders for Head-Media Spacing Variation Suppression in Ultralow Flying Air Bearings

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As the slider's flying height (FH) continues to be reduced in hard disk drives, the flying height modulation (FHM) due to disk morphology and interface instability caused by highly nonlinear attractive forces becomes significant. Based on the concept that the FH of a portion of the slider that carries the read/write element can be adjusted by a piezoelectric actuator located between the slider and suspension and that the FH can be measured by use of the magnetic readback signal, a new 3-degree of freedom analytic model and an observer-based nonlinear compensator are designed to achieve ultralow FH with minimum modulation under short range attractive forces. Numerical simulations show that the FHM due to disk waviness is effectively controlled and reduced.

***Index Terms*—Flying height modulation (FHM), hard disk drives, head–media interface, intermolecular and electrostatic forces, observer-based sliding mode control.**

I. Introduction

As THE flying height (FH) is reduced in a flying head slider to the sub 3-nm regime, the flying height modulation (FHM) induced by the disk morphology and dynamic instability due to short range attractive intermolecular and electrostatic forces [1] become more significant. This effect must be considered in the design of the air-bearing surface (ABS). In this paper, a novel controlled-flying proximity (CFP) slider is presented. A new 3-degree of freedom (DOF) analytic model is proposed to characterize the dynamics of the piezoelectric actuated slider. The air bearing parameters, such as stiffness and damping, are identified by a modal analysis method. Then, an observer-based nonlinear sliding mode controller is designed to compensate the short range attractive forces and to suppress the FHM of ultralow FH air-bearing sliders in proximity, in which the magnetic signal is used for real-time FHM measurement. The attractive forces are included in the model as a highly nonlinear term and the effect of disk morphology is modeled as unknown but bounded disturbances. The performance of the controller is investigated by numerical simulations.

II. Nonlinear 3-DOF Lumped Parameter Model of CFP Sliders

A schematic diagram of the CFP slider is shown in Fig. 1. The FH is about 20 nm in the off duty cycle and is reduced to about 3 nm during reading and writing. Fig. 2 shows the five-pad ABS design example used in this paper. The pole tip FH (FH_{pt}) is adjusted by the deflection of the cantilever actuator. The deflection is achieved by grounding the slider and applying a negative voltage to the top electrode of the central piezoelectric layer.

There are two modes of operation. In the passive mode, there is no external voltage applied to the piezoelectric layer so the active cantilever rests in the undeflected position. The pole tip FH in this case may be designed to be anywhere between 10 and 20 nm, depending on the ABS design. In the active mode, the cantilever is bent into close proximity of the disk with the application of a negative dc voltage to the middle portion of the piezoelectric material. Meanwhile, an ac computed control voltage is superposed on the dc voltage so that the FHM is minimized. The active mode is used only when the read/write head is in operation. The duty cycle for a practical head is rather low, as most of the time of the head is spent on nonread/write actions, such as latency, seeking, or idle. Thus, the wear and power consumption can be greatly reduced by simply operating the CFP in the passive mode. The air bearing pressure distributions in both modes are shown in Fig. 3, where the additional pressure peak is seen in (b) when the central pad is deflected into close proximity to the disk.

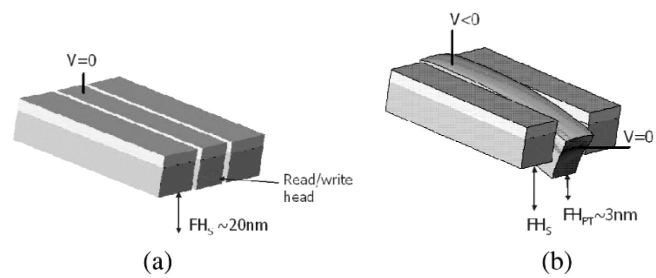

Fig. 1. Two operational modes of a CFP slider: (a) passive mode; (b) active mode.

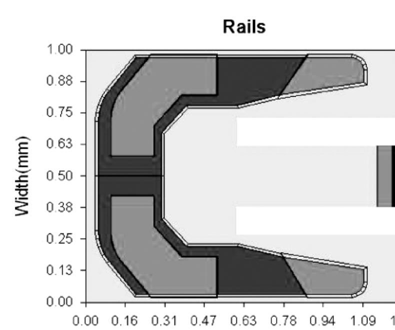

Fig. 2. ABS design of the CFP slider.

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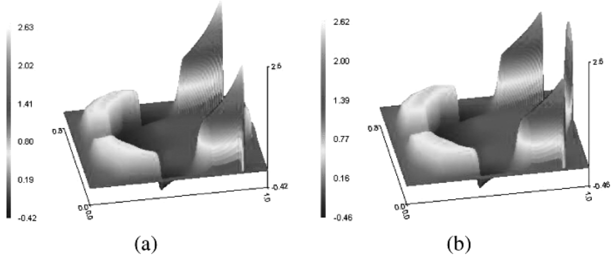

Fig. 3. Air pressure distributions of the ABS in Fig. 2. (a) passive mode and (b) active mode. The pole tip FH has been reduced from 20 to 2.35 nm. The unit of the color bar is atm.

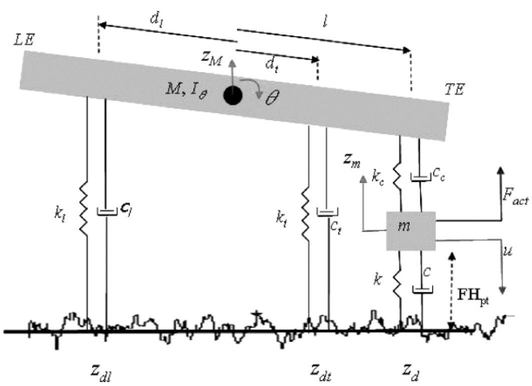

Fig. 4. Schematic diagram of 3-DOF dynamic model of CFP sliders.

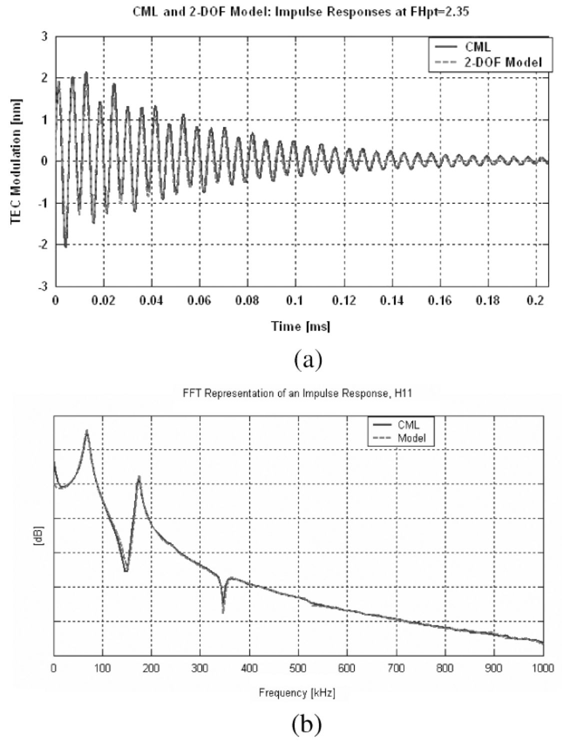

Fig. 5. (a) Impulse response and (b) Fourier transform of the CFP slider simulated by the 2-DOF model and the CML dynamic simulator.

As shown in Fig. 4, the CFP slider is modeled as a nonlinear 3-DOF lumped parameter model in which the cantilever actuator and the air bearing dynamics are modeled as 1-DOF and 2-DOF, respectively. The highly nonlinear short range forces, F_{act}, are modeled as the sum of intermolecular and electrostatic forces according to [1]. u is the control force, which will be calculated by the controller.

A. 1-DOF Lumped Model of the Piezoelectric Cantilever Actuator

The cantilever actuator, composed of a piece of piezoelectric material and a cutout portion of the slider, deflects under an electric voltage V and an external vertical force F exerted on the tip. V and F are the control voltage and the resultant force of the air bearing and short range forces, respectively. The constitutive equations that determine the tip deflection subject to a voltage and a force can be written as follows [2]:

$$\begin{aligned} \delta &= aF + bV \\ a &= \frac{1}{k_c} = \frac{4L^3}{E_p w t_p^3} \frac{\alpha\beta(1+\beta)}{\alpha^2\beta^4 + 2\alpha(2\beta + 3\beta^2 + 2\beta^3) + 1} \\ b &= \frac{3L^2}{t_p^2} \frac{\alpha\beta(1+\beta)}{\alpha^2\beta^4 + 2\alpha(2\beta + 3\beta^2 + 2\beta^3) + 1} d_{31} \\ \alpha &= \frac{E_s}{E_p}, \quad \beta = \frac{t_s}{t_p} \end{aligned} \tag{1}$$

where the subscripts s and p stand for the slider and piezoelectric materials, respectively. E and t are the Young's modulus and beam thickness, respectively. L and w represent the length and width of the composite beam. k_c is the bending stiffness of the cantilever. d_{31} is the piezoelectric coefficient.

B. 2-DOF Lumped Parameter Model of the Air Bearing and Its Parameter Identification

A linear modal analysis program developed by CML [3] is used to identify the air bearing parameters. A natural logarithm curve was found to be the best fit to the stiffness within the range of interest, giving a $k(\mathrm{FH})$ in units of newton/meters as a function of FH at the pole tip (PT) (FH) in units of nanometers

$$k(\mathrm{FH}) = \beta_k \cdot \ln(\mathrm{FH}) + \alpha_k \tag{2}$$

where the coefficients β_k and α_k for this fit are determined to be $-311\,456$ and $460\,671$, respectively.

The damping coefficient c is almost constant for FH between three and nine. A linear curve fit is applied to c for FH less than 3 nm, giving a $c(\mathrm{FH})$ in units of newton · second/meters as a function of FH at the PT (FH) in units of nanometers

$$c(\mathrm{FH}) = \beta_c \cdot \mathrm{FH} + \alpha_c \tag{3}$$

where the coefficients β_c and α_c for this fit are determined to be 0.0044 and 0.005, respectively.

This nonlinear 2-DOF model was compared to the CML Dynamic Simulator by computing the impulse responses of the slider. The results for FH of 2.35 nm are shown in Fig. 5 in both the time and frequency (fast Fourier transform) domains.

The results showed good agreement. The model has captured the air bearing frequencies and the nonlinearity.

III. Design of Nonlinear Compensators

The short range forces and disk waviness cause instability of the head–disk interface and increase the FHM. It is desirable to compensate the forces and to suppress the modulation by feedback control. Because of the nonlinear components and uncertain disturbance in the air bearing systems, an observer-based nonlinear sliding mode controller is used.

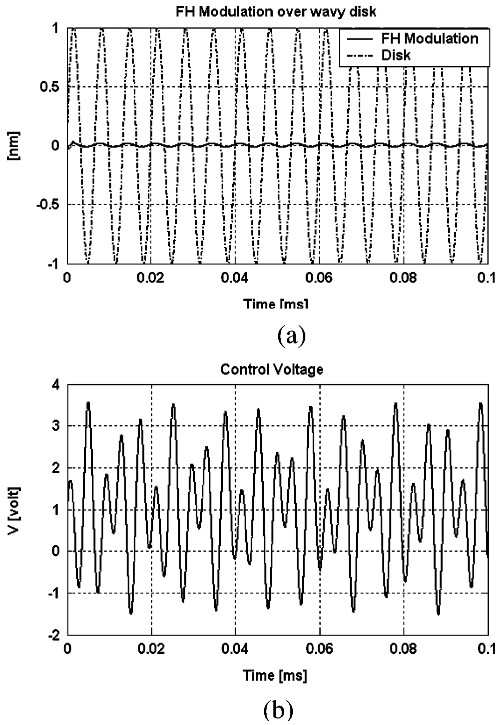

Fig. 6. (a) Results of FHM suppression of the CFP slider in the presence of intermolecular and electrostatic forces (0.5 V). The disk waviness wavelength is 0.1 mm. The disk rotation speed is 15 m/s; (b) the control voltage.

The equations of motion of the 3-DOF system can be transformed into a state-space representation as follows:

$$\begin{cases} \dot{x} = Ax + Bu + f(x) + f_d \\ y = Cx \end{cases} \tag{4}$$

where A, B, and C are matrices determined by the slider and air bearing parameters. $f(x)$ is the nonlinear term for the short range forces and f_d is the unknown disturbance due to disk waviness.

The control goal is to push the FHM to zero. If z_m is used as a state, this will be a tracking problem, $z_m \rightarrow z_d$. However, the future z_d is unknown. In order to resolve this, a new state z is defined as

$$z = z_m - z_d.$$

The states of the system are

$$x = [x_1 x_2 x_3 x_4 x_5 x_6]^T = [z_M \dot{z}_M \theta \dot{\theta} z \dot{z}]^T$$

where z_M, z_m, θ, and z_d are shown in Fig. 4.

The observer is designed as

$$\dot{\hat{x}} = A\hat{x} + Bu + f(\hat{x}) + L(y - C\hat{x}) \tag{5}$$

The error dynamic is obtained by subtracting $\dot{x}$ from $\dot{\hat{x}}$

$$\dot{\tilde{x}} = \dot{\hat{x}} - \dot{x} = (A\text{–LC})\tilde{x} - f_d. \tag{6}$$

The observer gain matrix L is chosen as in a Luenberger observer [4] so as to place the poles of $(A\text{–LC})$ at desired locations.

The sliding surface is defined as

$$s = \dot{\hat{x}}_5 + \lambda \hat{x}_5. \tag{7}$$

We then have

$$\begin{aligned} \dot{s} &= \dot{\hat{x}}_6 + \lambda \dot{\hat{x}}_5 \\ &= \frac{1}{m}[k_c\hat{x}_1 + c_c\hat{x}_2 - lk_c\hat{x}_3 - lc_c\hat{x}_4 \\ &\qquad - (k+k_c)\hat{x}_5 - (c+c_c)\hat{x}_6 + F_{\text{act}} - u] \\ &\quad + L_6(x_5 - \hat{x}_5) + \lambda[\hat{x}_6 + L_5(x_5 - \hat{x}_5)]. \end{aligned} \tag{8}$$

The control law is designed as

$$\begin{aligned} u = {} & k_c\hat{x}_1 + c_c\hat{x}_2 - lk_c\hat{x}_3 - lc_c\hat{x}_4 - (k+k_c)\hat{x}_5 \\ & - (c+c_c)\hat{x}_6 + F_{\text{act}} + m\lambda[\hat{x}_6 + L_5(x_5 - \hat{x}_5)] \\ & + mL_6(x_5 - \hat{x}_5) + m\eta s \end{aligned} \tag{9}$$

such that

$$\dot{s}s = -\eta s^2 < 0. \tag{10}$$

Equation (10) guarantees that s approaches zero based on Lyapunov theory and drives the estimated FHM $\hat{x}_5$ to zero exponentially according to (7)

Fig. 6 shows the results of FHM suppression and the required ac control voltages. It is seen that the FHM is reduced almost to zero even with the intermolecular force and an electrostatic potential of 0.5 V between the disk and slider.

IV. Conclusion

In this paper, a new 3-DOF dynamic model is proposed for a CFP slider, which is actuated by a layer of piezoelectric material. A linear modal analysis is used to identify the air bearing parameters. Good agreement is obtained for the air bearing dynamics between the model and the CML Dynamic Simulator. An observer-based nonlinear sliding mode controller is designed based on the model. Numerical studies show that an FH below 3 nm is achieved and the FHM due to disk waviness is effectively reduced in the presence of short range attractive forces.

Acknowledgment

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