Numerical and Experimental Analyses of Nanometer-Scale Flying Height Control of Magnetic Head With Heating Element

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Hard drives featuring sliders with active flying-height (FH) control using thermal expansion of a heating element have been recently introduced in products. This approach allows to actively compensate for static FH variations and achieves sub-3-nm clearance during read/write operation. This paper describes a nonlinear numerical model of a perpendicular magnetic recording head for accurate simulation of pole-tip protrusions and their effect on FH change under various conditions, such as at an elevated drive temperature, with the heater activated or during write operation. The model integrates an electrical-thermomechanical finite-element model of slider and a full air-bearing solver, and includes lapped pole-tip recession and slider/disk deformation due to air-bearing pressure. We are able to predict key parameters that are not easily measurable (e.g., minimum/reader/writer FH, different protrusion profiles for ambient temperature, heater actuation, and during writing). We also present novel experimental methods for measuring protrusion and clearance delta profiles with angstrom-level resolution. The modeling results are compared to experimental data under various test conditions showing excellent agreement. From this method, we are able to quickly evaluate and optimize different heater, head, and ABS designs.

***Index Terms*—Air-bearing surface (ABS), finite-element model, flying height (FH), hard-disk drives, head-disk interface (HDI), magnetic head slider, pole-tip protrusion.**

I. Introduction

FLYING-HEIGHT (FH) control using thermal actuation has been introduced recently in hard-disk drive (HDD) products as a new technique for compensating static FH variations of magnetic heads and reducing the risk of harmful head-disk contact. In such a drive, a resistive heating element (heater) is deposited near the read/write elements, and the gap FH is reduced by applying a current through the heater to deliberately induce heater pole-tip protrusion (H-PTP). Similar but less controllable protrusions are generated when the ambient temperature varies and/or when a write current passes through the write coil during writing. These temperature-induced-pole-tip protrusion (T-PTP) and write-induced-pole-tip protrusion (W-PTP) adversely reduce the FH considerably and may cause a reliability concern. Fig. 1 illustrates a schematic diagram of the slider attitude with and without protrusion, and the relationship between protrusion and clearance drop. Only a portion of the protrusion reduces the clearance due to the air-bearing pushback.

The cycle time of wafer and slider fabrication is long and some key parameters are not easily measurable, such as minimum and writer FH, and in-situ slider protrusion profiles. Therefore, it is of great importance to develop a model that can predict the actuation performance of different designs quickly and accurately to reduce product development time. For a flying slider, the thermal actuation is determined not only by the head/heater structure and materials, but also by the ABS-dependent thermal boundary condition, forming a complex nonlinear thermal-structural coupled-field problem Several publications have conducted modeling and/or measurements on PTPs [1]–[5], but none has included pole-tip recession (PTR) or the elastic compression of the slider and disk due to high air-bearing pressure. There was also limited model validation perhaps due to the difficulty of accurately measuring FH and protrusion bulge with high spatial resolution. This paper presents a comprehensive model and validates it by novel measurement methods under various conditions.

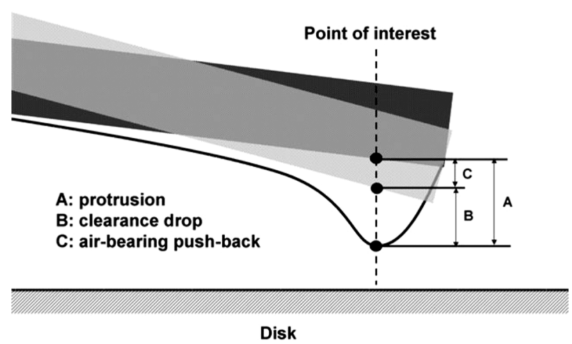

Fig. 1. Schematic diagram of the slider attitude when the heater is turned on and off. Only a portion of the protrusion produces clearance drop due to the air-bearing compensation.

II. Numerical Modeling

The numerical model created is a nonlinear model, which can accurately model T-PTP, H-PTP, W-PTP and the corresponding flying attitudes. We use a commercial software package (ANSYS) to create a 3-D finite-element model of the entire slider with a detailed head/heater structure, and then conduct electrical-thermomechanical analysis using velocity slip and temperature jump boundary conditions to formulate

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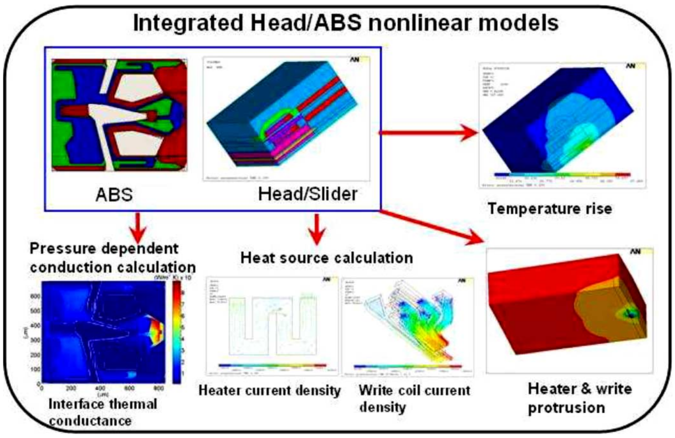

Fig. 2. Integrated head and ABS nonlinear model consisting of a calculation of: 1) current density and heat source; 2) interface thermal conductance; 3) temperature distribution; and 4) protrusion profile.

the heat transfer across the head-disk interface when the slider flies on a spinning disk (Fig. 2).

An iteration procedure, proposed earlier [4], [5], is used to obtain the equilibrium solution. The slider and disk deformation due to the air-bearing pressure is included since the pressure increases significantly when the FH is reduced to a sub-5-nm regime. Another critical parameter, PTR, created by lapping and etching processes, is also included in the model. We also performed T-PTP, H-PTP, and W-PTP simulation with a nonflying boundary condition in which the slider is attached to a large aluminum plate, and electrical current is applied through the heater or the write coil. Since the air bearing does not play a role in such a condition, we can verify the finite-element model with profilometry and quickly compare different heater designs without iteration.

III. Experimental Methodology

A. Nonflying Protrusion Measurement

We use the Wyko (interferometer) tool to measure the protrusions in the nonflying condition in which the slider is attached to an aluminum plate, and the protrusion profile is obtained by aligning and taking the difference of the two images when the heat source is turned on and off.

B. Optical FHT Measurement

Three-wavelength interferometry, such as the dynamic flying height tester (DFHT), has been routinely used to measure FH. However, the light spot of conventional tools is $\sim$20 μm, which is not sufficient to resolve the detailed protrusion in the element area. To measure the FH and clearance change profiles with high resolution in the flying condition, we have developed a new method based on the principle of a conventional FH tester. Instead of using a photo detector, we use the charge-coupled device (CCD) sensor (Fig. 3). The spatial resolution is $\sim$1.25 μm, which is determined by the CCD pixel size and optical lens magnification.

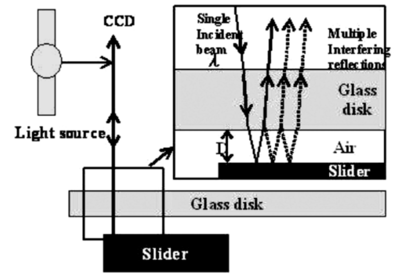

Fig. 3. Optical FH measurement with the CCD sensor with spatial resolution $\sim$1.25 μm.

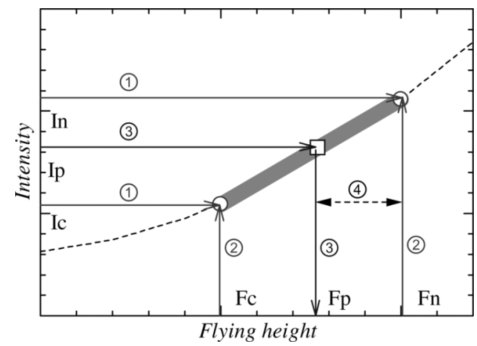

Fig. 4. Measurement flow of the FH profile and clearance change.

The procedure of measuring the FH profile and head-disk clearance change is illustrated in Fig. 4 and explained as follows: 1) measure two or more intensities of the flying head without protrusion at an area with known n and k; 2) derive the relationship between the intensity and FH; 3) measure intensity with protrusion and convert it to FH; and 4) calculate the clearance change by the difference between the cases with and without protrusion as expressed in (1)

$$\Delta\text{FH} = F_n - F_p = (F_n - F_c) \times [(I_n - I_p)/(I_n - I_c)] \quad (1)$$

where ΔFH is the delta clearance; F and I are the flying height and intensity, respectively; and subscripts n, p, and c denote normal, protrusion, and calibration conditions, respectively.

This measurement is carried out for all of the points over the area of interest. In general, FH measurements depend on the n and k (optical offset) of the material being measured, but Δ FH is independent (to the first order) of the optical offset, which is cancelled when two FH measurements are subtracted.

C. Wallace Spacing Change and Touch-Down Power

The FHT measurement is useful to obtain 3-D images of an entire protrusion bulge, but the use of a glass disk may cause a different touch-down characteristic. We use a Guzik spin-stand to calibrate H-PTP by increasing the heating power until a touch-down is detected by the acoustic-emission (AE) signal. We calculated the slider to disk spacing change using the Wallace magnetic spacing formula at various levels of thermal protrusion

$$\Delta\text{FH} = \frac{\lambda}{2\pi} \ln\left(\frac{A_1}{A_2}\right) \quad (2)$$

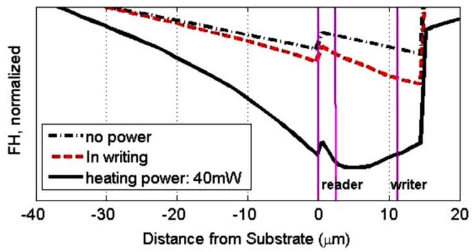

Fig. 5. Example of comparison of FH profiles along the center line of ABS with and without heating power, and in writing. The step at 0 μm is the PTR. (reader: MR sensor; writer: write gap) (a) T-PTP; ambient temperature ($\Delta T = 30°C$). (b) H-PTP; dc current through heater: 20 mA. (c) W-PTP; dc current through write coil: 100 mA.

where λ is the written wavelength and A_1/A_2 is the amplitude ratio of the read-back signal. We typically used short wavelengths (50 nm to 100 nm) for improved resolution.

IV. Results and Discussions

Fig. 5 shows a comparison of the FH reduction along the center line of the ABS with 40-mW heating power and during writing. These data clearly show that the two protrusion bulges are different, and the MR sensor (reader) and write gap (writer) protrude differently under different conditions. The step at 0 μm of the initial FH profile is PTR, which can be measured by an atomic force microscope (AFM) and included in the static ABS model. PTR greatly affects the relative FH of key locations and the contact point.

Comparisons between simulation and measurements were made in nonflying and flying conditions. Fig. 6 shows the results of the nonflying case. The simulation shows excellent agreement with the measurements for the entire bulge profiles at all three conditions.

Fig. 7 shows a comparison of the clearance change between the simulation and FHT with a power of 65 mW. It is seen that the model prediction agrees reasonably well with the FHT over the entire shape of the bulge. The clearance drop of the reader predicted by the model is ~0.5 nm more than the average value of measured data, which has a standard deviation of ~0.56 nm.

In the Guzik spin-stand test, as we increased the power to the heater, we measured the read-back signal amplitude and AE signal to monitor the head-disk contact. Fig. 8 shows the comparison of the clearance drop at the reader versus heating power at different radial positions. The simulation prediction agrees well with the experiment at all of the radii. We observe that the clearance drop is not proportional to the power. Instead, a quadratic fit has been found to best fit the curves. This nonlinearity is due to stiffer air bearing and more effective heat loss through air bearing when the poletip approaches the disk. The simulation of minimum FH shows the touchdown powers are approximately 80 mW, 110 mW, and 120 mW at the inner-, mid-, and outer-diameter (ID, MD, and OD), respectively, which agrees well with the AE measurement (Fig. 9). It is observed that the touchdown power at the ID is much smaller than that at the OD even though the FH is quite flat across the disk. Such a difference is mainly attributed to the difference in actuation efficiency of the ABS (expressed in nanometers per megawatt) as confirmed by the clearance data in Fig. 8.

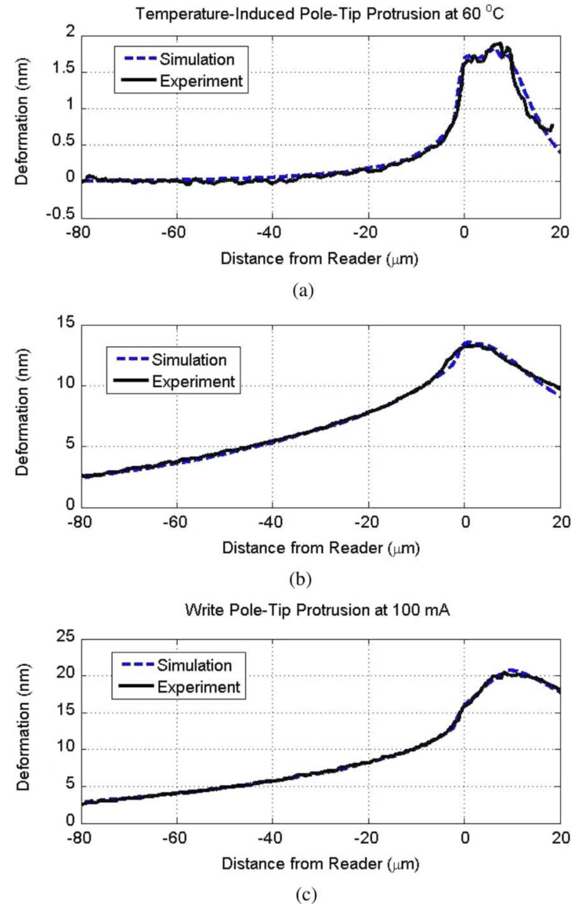

Fig. 6. Comparison of nonflying protrusion profiles along the centerline of the slider length under three conditions: 1) higher ambient temperature; 2) dc current through the heater; and c) dc current through the write coil.

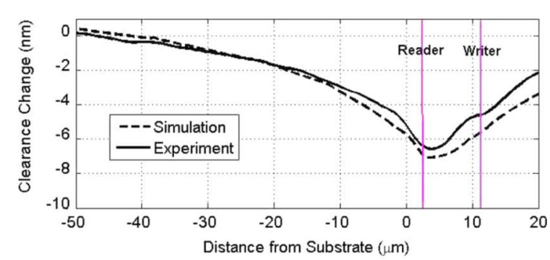

Fig. 7. Comparison of the clearance change between the simulation and optical FHT measurement under the flying condition (heater power: 65 mW).

The effect of slider and disk deformation on the FH due to the air-bearing pressure is shown in Fig. 10. The minimum FH of the case with the rigid disk and slider is ~0.5 nm lower than that of the more realistic one, and the effect of the slider is more noticeable than that of the disk, even though the disk may deform up to about 2 nm (glass disk). The spatial extent of the poletip protrusion and disk deformation with a heating power of 40 mW is shown in Fig. 11. The amount of disk deformation is mainly determined by the material. No significant effect of media overcoat type is noticed. However, only a portion of the disk and slider compression contributes to the FH increase because of the self-compensation of an air bearing, that is with

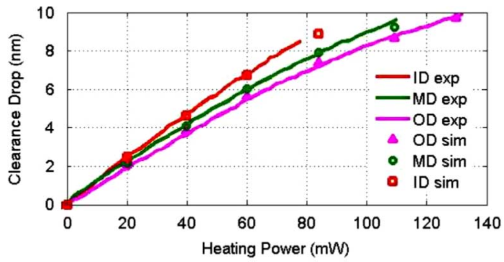

Fig. 8. Comparison of the clearance drop at the reader location versus heating power at three radial positions. The experiment was conducted on a Guzik spinstand. (a) Simulation. (b) AE measurement.

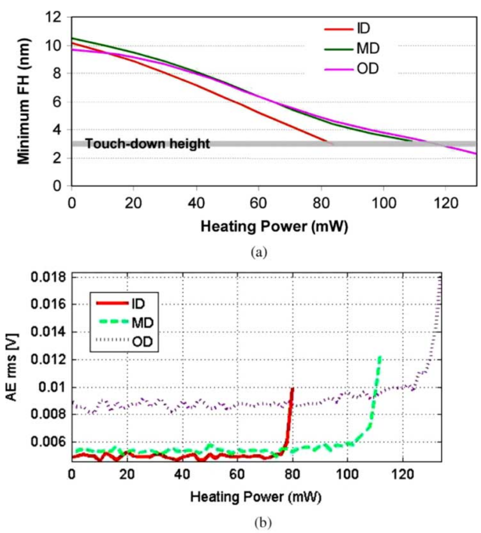

Fig. 9. (a) Simulation of the minimum FH shows the touch-down powers are approximately 80 mW, 110 mW, and 120 mW at the ID, MD, and OD, respectively, which agrees well with the AE measurement in (b).

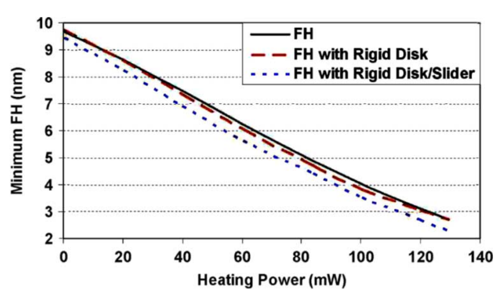

Fig. 10. Effect of slider and disk deformation due to the air-bearing pressure. (a) Pole-tip protrusion. (b) Disk deformation.

reduced FH, the air bearing becomes stiffer and produces more lift.

V. Conclusion

This paper presents a head/ABS nonlinear model, which solves an electrical-thermomechanical finite-element and air-bearing coupled-field problem. The model can be very useful in quickly and accurately evaluating head/heater/ABS performance, and greatly reduces the cycle time of product development. Several novel experimental techniques were also developed for measuring the protrusion bulge, clearance drop profile, and touch-down power with high resolution and repeatability. The model was shown to agree reasonably well with the measurements, both qualitatively and quantitatively.

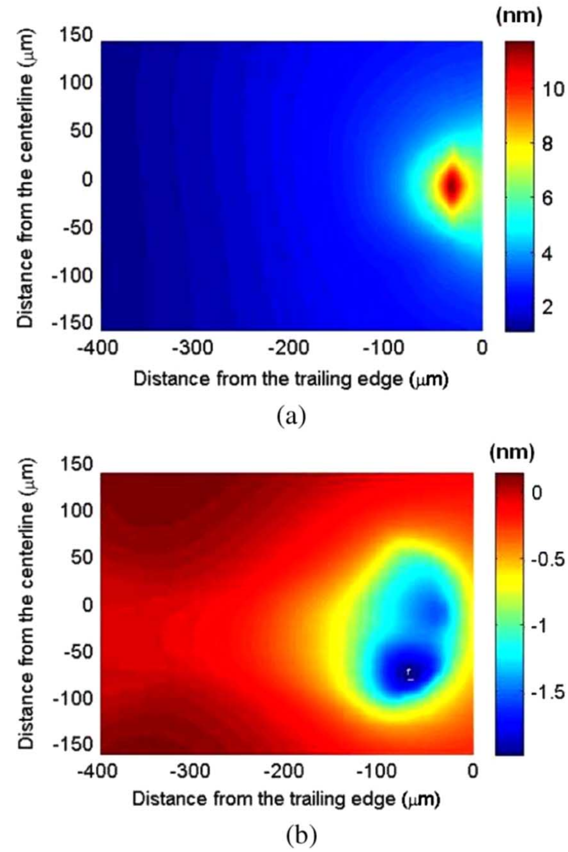

Fig. 11. Slider and disk deformation due to the air-bearing pressure at OD (40-mW heating power).

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