Near contact thermal flying height control in hard disk drives

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The flying height in hard-disk drives needs to be reduced below 2 nm to allow storage densities beyond 1 Tb/in [1]. Thermal flying height control (TFC) sliders have been introduced to control the spacing between the read and write element and the disk (magnetic spacing) [2]. TFC sliders feature embedded thin-film resistive heater elements in the slider trailing edge (see Fig. 1). Providing electric power (heater actuation) heats up the nearby material which expands due to the heat, causing a thermal deformation at the location of the read and write element. Typically, TFC sliders are being used in a quasi-static fashion by supplying the heater with a constant level of heater power to compensate for static spacing variations. The level of heater power is adjusted according to changes in environment and disk operation (i.e., reading vs writing). There are, however, several factors that cause the flying height to change more dynamically around the circumference of the disk. These dynamic flying height changes result from disk waviness, disk distortions due to clamping, and slider vibrations induced by turbulence or even external shocks [3]. A dynamically controlled TFC slider can be used to optimally tune magnetic spacing while avoiding slider-disk contacts.

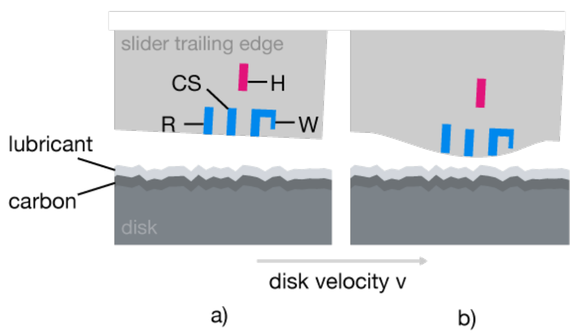

Fig. 1. Schematic depiction of the operation of a thermal flying height control (TFC) slider. Head-disk interface showing the trailing edge of a TFC slider and the disk in a) its default state, and b) under heater actuation. The schematic depiction shows the resistive heater element (H), the contact sensor (TCS), the read element (R), and the write coil (W).

In recent years, thermal contact sensors (TCS), or touchdown sensors (TDS), have been implemented in TFC sliders, allowing detection of head-disk contacts and mapping of disk topography or disk defects [8], [9]. Thermal contact sensors are temperature sensitive resistive elements and located between the read and write element as indicated in Fig. 1.

In this study, we propose a method for minimizing flying height variations of TFC sliders. The method utilizes the embedded thermal contact sensor to estimate the flying height error, and model the dynamics of the TFC slider. First, we identify the static and dynamic behavior of the thermal contact sensor as a function of heater power. Based on the static and dynamic behavior of the system, the optimal power input profile to the heater is calculated using a convex optimization technique similar to Boettcher et al. [6]. The proposed approach is verified experimentally on a spin-stand tester and used to illustrate how flying height variations can be reduced dynamically.

III. STATIC CHARACTERIZATION OF THERMAL CONTACT SENSORS

A. Mean and standard deviation trends

To illustrate the sensitivity of the TCS, we show the sensor voltage as a function of heater power in Fig. 4 at a radial position of 27 mm on the disk. We observe from Fig. 4 that the standard deviation of the sensor voltage (solid curve) is nearly constant for heater powers up to 130 mW. For heater powers larger than 130 mW, a sudden increase in the sensor standard deviation is observed. The onset of slider-disk contact occurs at 134.5 mW (vertical dashed line). The dashed curve in Fig. 4 represents the mean of the sensor voltage. The sensor mean voltage increases initially, reaches a local maximum at 122.5 mW, and decreases thereafter.

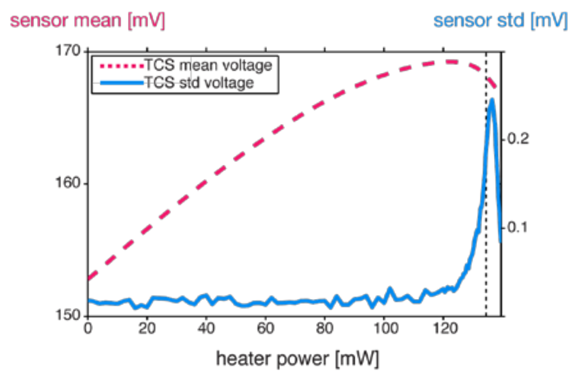

Fig. 4. TCS voltage output versus heater input power. Head-disk contact is detected at 134.5 mW according to the sensor standard deviation (std) as indicated by the vertical dashed line.

Fig. 4 illustrates that the mean sensor voltage creates a measurable signal and becomes 'active' in close proximity with the disk – the exact operating condition where the flying height should be for minimal magnetic spacing and largest read-back signals. However, spacing variations need to be reduced as much as possible to avoid intermittent contact at these spacing levels. The resistance and hence voltage output of the sensor are temperature dependent. The voltage output of the sensor, V_{TCS}, may therefore be expressed as a function of

$$V_{TCS} = f(I_{TCS}, P_{heater}, q) \qquad (1)$$

in which I_{TCS} denotes the bias current for driving the sensor, P_{heater} is the electrical power applied to the heater for adjusting the head-disk spacing, and q refers to the heat flux in the neighborhood of the sensor which is a function of the head-disk spacing.

B. Compensation for heater power

To use the sensor as an estimate for changes in flying height, it is desirable to eliminate the effect of heater power P_{heater} from equation (1). To do this, we apply a third order polynomial curve fit to the sensor mean voltage over a specified curve fit range and subtract the curve fit from the sensor mean voltage. The curve fit y_{fit} is described by

$$y_{fit} = a_0 + a_1 P_{heater} + a_2 P_{heater}^2 + a_3 P_{heater}^3,$$

$$P_{heater} \in [0, k \cdot TDP] \; mW \qquad (2)$$

in which a_0, a_1, a_2, a_3 are the coefficient of the third order polynomial curve fit and k denotes the curve fit range expressed as a percentage of the touch-down power TDP (i.e. the onset of slider-disk contact indicated by the vertical dashed line in Fig. 4).

IV. DYNAMIC MODELING

In order to compute the optimal feedforward heater profile via convex optimization, a dynamic model of the thermal actuator is needed. The step-based realization algorithm [6] allows the estimation of a linear time invariant discrete time model of the thermal actuator from experimentally obtained step-response data. The step response data is created via a step-wise excitation signal applied to the TFC and measuring the TCS signal around the operating condition of P_0.

To obtain a measure of the flying height error over one disk revolution, the following procedure was used: First, the average sensor voltage V_{TCS} of 20 disk revolutions was acquired. Thereafter, the curve fit y_{mean} of the mean voltage was subtracted from the instantaneous sensor voltage V_{TCS} via linear interpolation. The resulting curve was then compared to the control curve set-point r_{cc}, yielding error signal ε

$$\varepsilon = r_{cc} - (V_{TCS} - y_{fit}) \quad (3)$$

The error signal ε of 20 disk revolutions at 16.67 kHz is shown in Fig. 10. The dots represent the average of 20 continuous disk revolutions and the solid lines indicate the corresponding standard deviation. It can be seen that the error signal varies repetitively with every disk revolution.

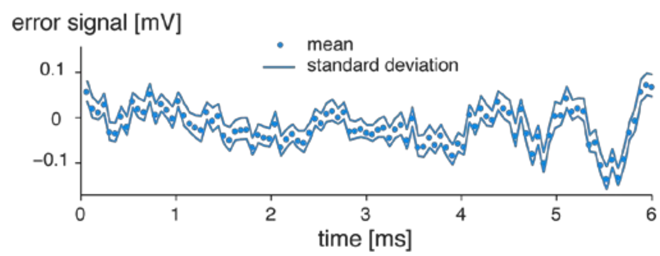

Fig. 10. Error signal versus time for one disk revolution (average of 20 consecutive disk revolutions).

We now estimate the dynamics between heater power and error signal using the following procedure: First, the average error signal of 20 disk revolutions, denoted ε_0, is acquired while supplying the heater with the desired DC operating power P_0 = 130.5 mW. Next, the experiment is repeated while modulating the heater input with rectangular pulses, yielding ε^* . We then subtract ε_0 rom ε^* to obtain the change in error signal due to applying a step in heater power.

Fig. 11 shows the error signal vs time for various steps in heater power. Using the realization algorithm in [6], a second order discrete time model was identified for each set of step response data. The simulated system response is indicated by black dashed lines in Fig. 11. We observe that the identified second order systems are in good agreement with the measured step response data. Moreover, the dynamics of the model characterized by the time constants of the identified systems appear to be on the same order.

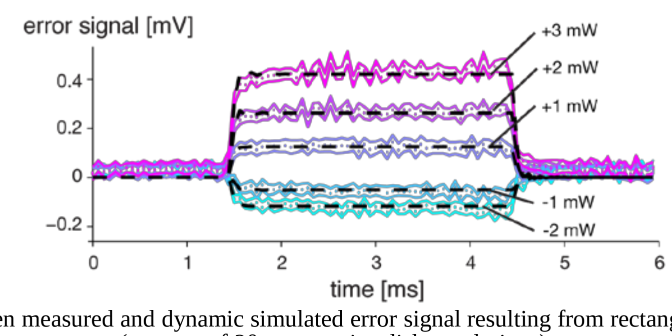

Fig. 11. Comparison between measured and dynamic simulated error signal resulting from rectangular pulses in heater power (average of 20 consecutive disk revolutions).

V. COMPUTING THE OPTIMAL HEATER INPUT PROFILE

The flying height error can be eliminated by actuating the heater element in a way so that the induced flying height changes match the inverse of the flying height error. As Boettcher et al. [6] pointed out, this problem can be stated as a convex optimization problem where the flying height modulation is minimized in a 2-norm sense. The optimization algorithm will be discussed in the full paper, whereas experimental results are presented below.

The average error signal of 20 disk revolutions in Fig. 10 shows significant high-frequency variations in flying height. As the bandwidth of the thermal actuator is limited (see Fig. 12), accounting for these high frequency variations in the error signal would result in large high frequency control inputs to the thermal actuator which is undesirable. A non-causal lowpass filter is therefore applied to limit the bandwidth of the error signal to 5 kHz as shown in Fig. 13.

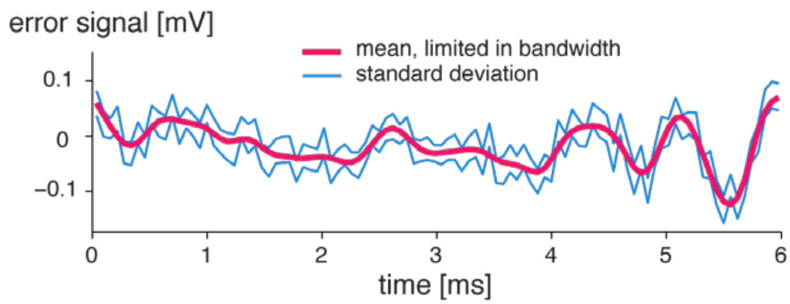

Fig. 13. A non-causal filter was applied to the average error signal of 20 disk revolutions to limit the bandwidth of the signal to 5 kHz in order to avoid large high frequency control signals.

The optimal feedforward heater input profile for minimizing flying height variations was computed using the CVX software package [12], [13]. The operating DC power was chosen to be 4 mW below the onset of slider-disk contact, i.e. P_0 = 130.5 mW. After completing the optimization procedure, the calculated power profile was applied to the heater element and the corresponding error signal of 20 disk revolutions was measured. Fig. 14 shows a) the heater power versus time, and b) the error signal versus time over the duration of one disk revolution. The dots in Fig. 14 b) represent the mean of the error signal of 20 continuous disk revolutions, and the solid lines represent the standard deviation of the error signal.

Our feedforward compensation targets the repeatable variations in flying height up to frequencies of 5 kHz. In fact, the error signal shown in Fig. 14 b) shows significantly less variations compared to the uncontrolled case shown in Fig. 10. In particular, the difference between the maximum and the minimum value is reduced from $2.1 \cdot 10^{-4}$ V to $1 \cdot 10^{-4}$ V and the standard deviation of the mean error signal is reduced from $4.1 \cdot 10^{-5}$ V to $1.8 \cdot 10^{-5}$ V. These results demonstrate that the proposed method is a promising technique for reducing variations in flying height in close proximity utilizing the embedded thermal contact sensor.

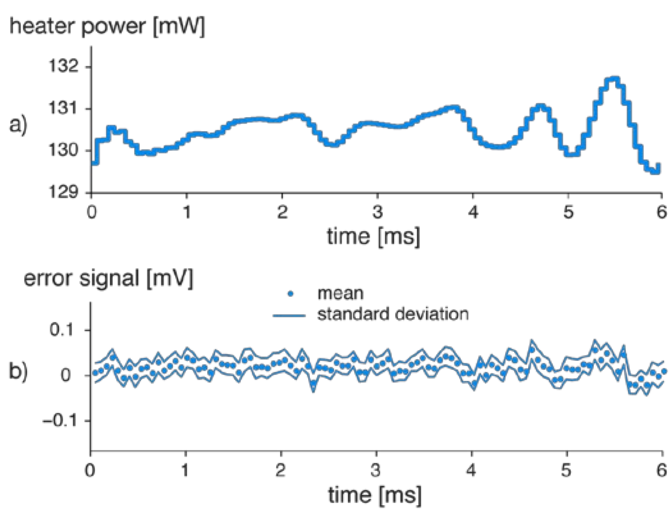

Fig. 14. a) Heater power versus time, and b) error signal versus time while applying the optimal feedforward profile to the heater (average of 20 consecutive disk revolutions).

VI. CONCLUSIONS

The optimization approach was verified experimentally, showing that the proposed approach reduces the difference between the maximum and the minimum value of the TFC measurements by a factor of two, indication a twofold reduction of flying height variations. Future work will involve independent measurements of the sub-nanometer flying height variations to verify the validity of using the TCS and control of the TFC for sub-nanometer flying height control.

VII. ACKNOWLEDGEMENTS

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