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TECHNICAL PAPER

Contact and temperature rise of thermal flying height control sliders in hard disk drives

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Abstract Contact and interfacial temperature rise upon slider-disk contact in hard disk drives is investigated using thermal flying height control (TFC) sliders. To achieve contact, the heater element of the TFC slider is energized with constant and square wave voltage input profiles with increasing bias. The temperature rise during slider-disk contact is estimated from the resistance change at the read element using auxiliary calibration measurements. Laser Doppler vibrometer measurements show that vertical gimbal vibrations occur if the power input to the heater exceeds a critical level, seemingly related to slider-disk contact. During contact, the same frequencies occur in the spectrum of the resistance of the read element and the vertical gimbal velocity. Furthermore, it is found that the gimbal is excited at additional frequencies for a square wave heater input profile compared to a constant heater input profile.

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1 Introduction

Since the flying height in hard disk drives (HDDs) has decreased to only a few nanometers, intermittent contacts between slider and disk are increasingly more likely to occur. Currently, the head-disk spacing in commercially available HDDs is on the order of 2 nm (Shimizu et al. 2011). To achieve an areal density of 5–10 Terabit per square inch, a physical spacing on the order of 0.25 nm is required (Zheng and Bogy 2010). Intermittent contact between slider and disk could result in wear, frictional heating, read/write element degradation or lubricant interactions at the head-disk interface (HDI).

Local temperature rise exceeding the Curie temperature due to frictional heating might result in the erasure of magnetic information (Suk et al. 2000). The temperature rise during contact is of very short duration and generally referred to the term flash temperature (Stachowiak and Batchelor 2005). In numerical studies, flash temperatures on the order of 1,000 K have been simulated (Ovcharenko et al. 2010; Yu et al. 2007). Since the resistance of the read and write element is temperature dependent, frictional heating due to slider-disk contact causes a change in the resistance of the read and write element as well.

Intermittent contact between slider and lubricant can result in lubricant rippling, lubricant pick-up and lubricant transfer (Canchi and Bogy 2011a, c). As lubricant is redistributed over the disk, the lubricant thickness becomes non-uniform and the critical flying height at which touch-down occurs may be affected (Shimizu et al. 2009). It has also been found that lubricant contact excites vertical, down- and off-track vibrations of the slider with the largest displacement in the off-track direction (Canchi and Bogy 2011b; Liu et al. 2009; Ng et al. 2009; Vakis et al. 2009; Xu et al. 2009; Zhang et al. 2009).

To investigate contacts between slider and disk, it is convenient to reduce the rotational speed of the disk or to reduce the ambient pressure surrounding the disk drive. However, contacts between slider and disk due to reduced velocity or reduced ambient pressure are substantially different from contacts when actuating the heater element of thermal flying height control sliders.

Thermal flying height control (TFC) sliders have been implemented in commercial HDDs since 2007 (Schultz 2007). TFC sliders contain a heater element close to the read and write element in the trailing edge of the slider. Energizing the heater element causes a thermal deformation of the bottom surface of the slider, thereby reducing the flying height between the read and write element and the disk. TFC sliders have allowed a reduction of the head-disk spacing to the order of several nanometers. Since the read element is an extremely sensitive sensor, it has been also used for the detection of slider/disk contacts (Liu et al. 2009; Ng et al. 2009; Zhang et al. 2009).

In the present study, we investigate contact between a commercially available TFC slider and a magnetic disk. To achieve contact, the heater element of the TFC slider is energized with constant and square wave input profiles with increasing bias. Laser Doppler vibrometry is used to study the dynamics of the vertical gimbal velocity. The temperature rise during slider-disk contact is estimated from the resistance change at the read element using auxiliary calibration measurements.

2 Experimental set-up and procedure

A schematic of the experimental set-up used in this investigation is shown in Fig. 1. The set-up consists of a commercially available HDD with a cutout in the top cover, a 3D laser Doppler vibrometer (3-D LDV) and an oscilloscope for high-speed data acquisition. A printed pre-amp circuit board was designed and built to access the read, write and heater element. To measure the respective resistance values, the write element was biased with a current of 20 mA, whereas the read element was biased with a voltage of 100 mV. The input to the heater of the TFC slider was generated using a dynamic signal generator. To monitor the resistance of the heater, the voltage over a known resistance in series with the heater element was measured as indicated in Fig. 1. For the investigation of the vertical gimbal vibrations and the resistance change at the read and write element, constant and square wave voltage profiles were applied to the heater. The resistance changes of the read and write element as a function of heater power were measured along with the vertical gimbal velocity using an LDV. In addition, the resistance change of the read element was measured for the following three cases: (a) the slider was removed from the disk, (b) the slider was loaded on the stationary disk and (c) the slider was flying over the disk. To estimate the temperature rise during contact, auxiliary resistance calibration measurements were carried out in a temperature-controlled environment.

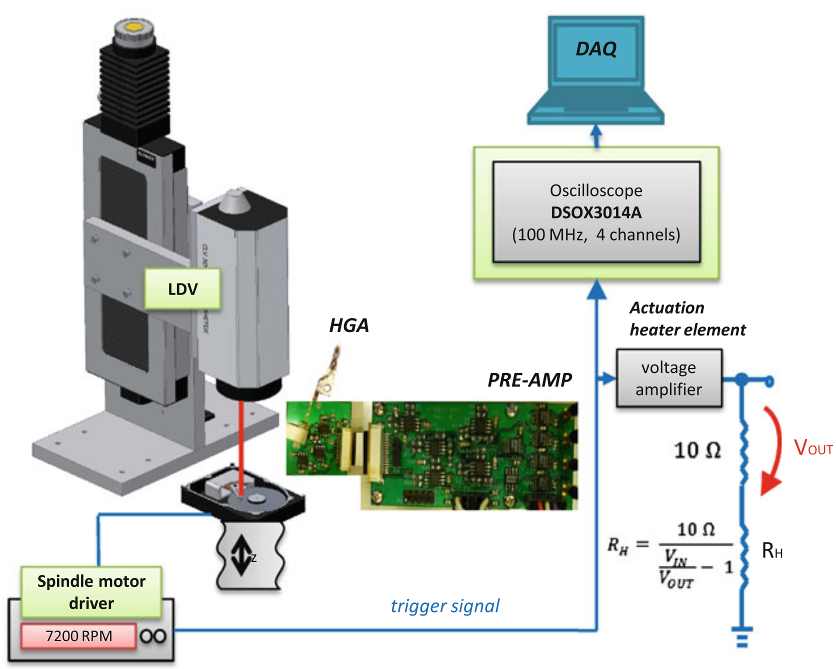

Fig. 1 Experimental set-up

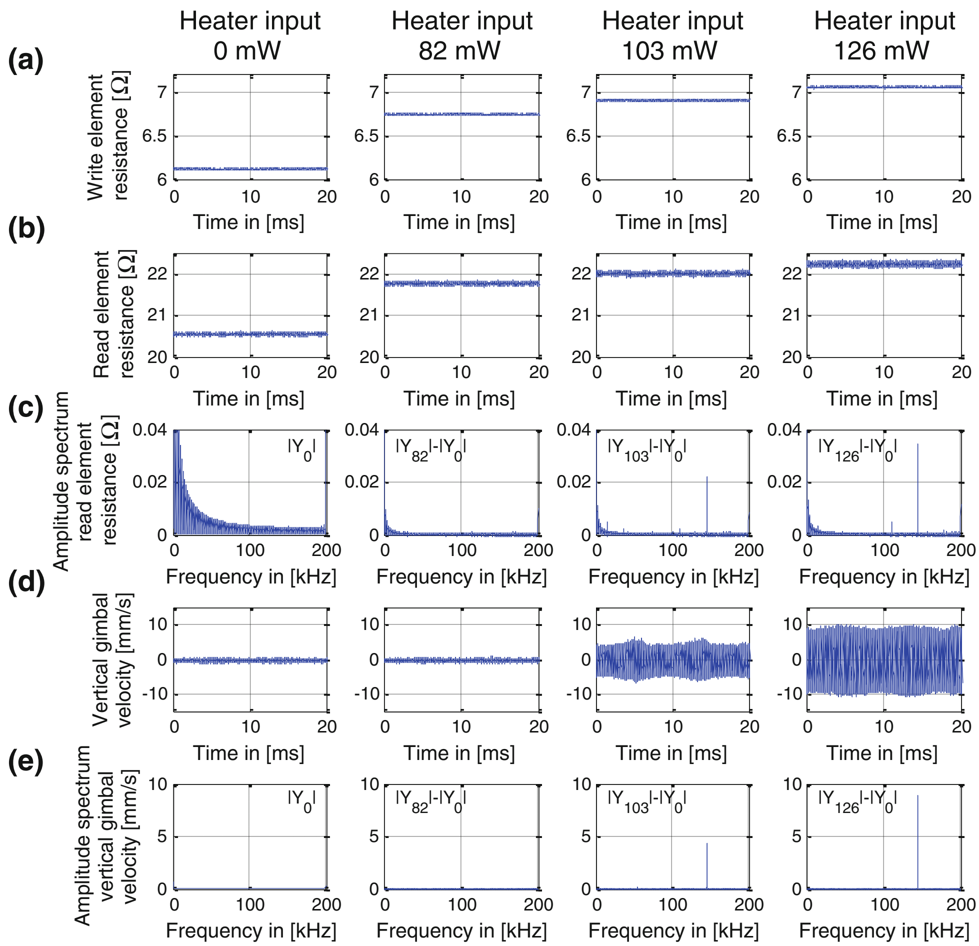

Fig. 2 **a** Write element resistance, **b** read element resistance, **c** change in frequency spectrum of the read element resistance after subtracting the resistance spectrum $|Y_0|$ at 0 mW, **d** vertical gimbal velocity and **e** change in frequency spectrum of the vertical gimbal velocity after subtracting the spectrum $|Y_0|$ at 0 mW for a constant heater input of 0 mW (*1st column*), 82 mW (*2nd column*), 103 mW (*3rd column*) and 126 mW (*last column*)

3 Experimental results

3.1 Contact for constant and square wave heater input profiles

3.1.1 Contact for constant heater input profile

A constant voltage input profile was applied to the heater element of a TFC slider and increased in small increments. The results for a power input to the heater of 0 mW (1st column), 82 mW (2nd column), 103 mW (3rd column) and 126 mW (last column) are depicted in Fig. 2. The first and second row of Fig. 2 show the resistance of the write and read element, respectively, as a function of power input to the heater. Figure 2c shows the change in the amplitude spectrum of the read element resistance |Y|, obtained by subtracting the spectrum observed at zero heater power $|Y_0|$. The frequency spectrum of the write element is not shown since no significant changes were observed with increasing heater input. The vertical gimbal velocity is depicted in Fig. 2d and the last row, Fig. 2e, shows the change in the amplitude spectrum of the vertical gimbal velocity after subtracting the spectrum for the heater input of 0 mW.

We observe from Fig. 2a, b that the write and read element resistance increases with increasing power input to the heater. Furthermore, we observe that the standard deviation of the read element resistance increases with increasing heater power (Fig. 2b). Figure 2c shows that the spectrum of the read element resistance does not exhibit any isolated resonance frequencies for a power input to the heater of 0 and 82 mW, while a well-defined frequency peak at 144 kHz is present for a heater input of 103 and 126 mW, respectively. Looking at the frequency spectrum of the vertical gimbal velocity in Fig 2e, we observe that frequencies in the 144 kHz range are also absent for a heater power of 0 and 82 mW, while a well-defined peak is present in the frequency spectrum at 144 kHz for a heater

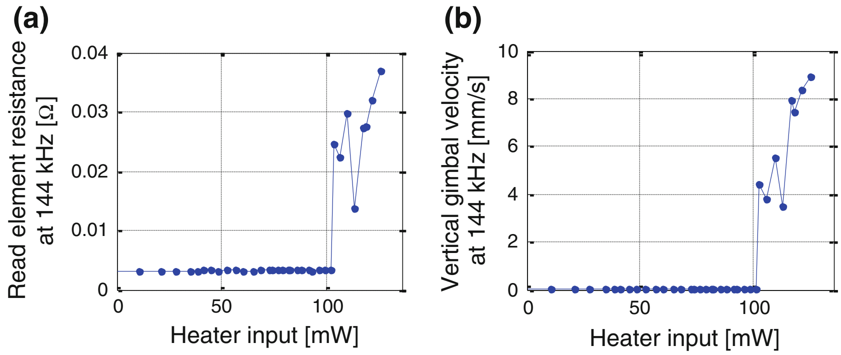

Fig. 3 Amplitude of the read element resistance and vertical gimbal velocity at 144 kHz as a function of power input to the heater for a constant heater input profile

power of 103 and 126 mW. It is apparent that the slider is vibrating and that contacts between slider and disk occurs.

The amplitude of the read element resistance and the vertical gimbal velocity at 144 kHz are summarized as a function of heater power in Fig. 3. We observe from Fig. 3 that the read element resistance increases at the same heater power (>102 mW) at which a strong increase in the amplitude of the vertical gimbal velocity is observed (>102 mW). It is likely that the occurrence of a peak in the spectrum of the vertical gimbal velocity is related to contacts between slider and disk. A frequency of 144 kHz could correspond to the first pitch mode frequency of the air bearing of the slider or to higher order gimbal vibrations. The observation that the read element resistance and the vertical gimbal velocity are correlated suggests that the resistance change is related to contacts between slider and disk. Clearly, if the slider makes contact with the disk, frictional heating is expected to occur which would result in an increase in resistance.

3.1.2 *Contact for square wave heater input profile*

In a second experiment a square wave voltage profile with a step size of 1 V was applied to the heater element and the bias voltage was increased in small increments. The results for a mean power input to the heater of 5 mW (1st column), 83 mW (2nd column), 104 mW (3rd column) and 125 mW (last column), respectively, are depicted in Fig. 4. The first and second row of Fig. 4 show the resistance of the write and read element, respectively, as a function of power input to the heater. Figure 4c shows the change in amplitude spectrum of the read element resistance, obtained by subtracting the spectrum at 5 mW heater power, denoted as $|Y_0|$. The vertical gimbal velocity is depicted in Fig. 4d. Figure 4e shows the change in the amplitude spectrum of the vertical gimbal velocity after subtracting the spectrum for a heater input of 5 mW. In the last row, Fig. 4f, the time frequency plot of the vertical gimbal velocity is shown.

Similar to the experiment with constant heater input, we observe an increase in the write and read element resistance with increasing power input to the heater (Fig. 4a, b). Also, the standard deviation of the read element resistance increases with increasing heater input (Fig. 4b). In Fig. 4c we see that frequency peaks are absent for a heater input of 5 mW, while a well-defined frequency peak at 144 kHz occurs in the spectrum of the read element resistance for a heater power of 83 mW or higher. From Fig. 4e we observe that the same frequency at 144 kHz is also present in the frequency spectrum of the vertical gimbal velocity. For a heater input of 104 mW, the gimbal is excited at both 144 and 155 kHz which can be seen in the third column of Fig. 4e. Looking at the time–frequency plot of the vertical gimbal velocity for a mean heater power of 104 mW (Fig. 4f), we see that the gimbal is first excited at 155 kHz and then at 144 kHz. It can be seen in Fig. 4d that the amplitude of vibrations at 144 kHz is larger than the amplitude of vibrations at 155 kHz. For a heater input of 104 mW we observe from Fig. 4a, b that stronger vibrations of the gimbal correlate with an increase in the resistance of the write and read element resistance, respectively. Frequencies of 144 and 155 kHz can also be seen in the spectrum of the read element resistance as shown in Fig. 4c. If the heater input is increased to 125 mW, vertical gimbal vibrations at 55, 63 and 144 kHz are observed (last picture of Fig. 4e, f). All three frequencies can also be seen in the frequency spectrum of the read element resistance as depicted in Fig. 4c.

The amplitudes of the frequencies at 54, 63, 144 and 155 kHz as a function of power input to the heater are shown in Fig. 5. The first row shows the amplitudes spectrum of the read element resistance while the second row shows the amplitude spectrum of the vertical gimbal velocity.

We observe from Fig. 5a, b that frequencies at 54 and 63 kHz occur in the read element resistance if the mean power input to the heater exceeds 122 mW. Figure 5c

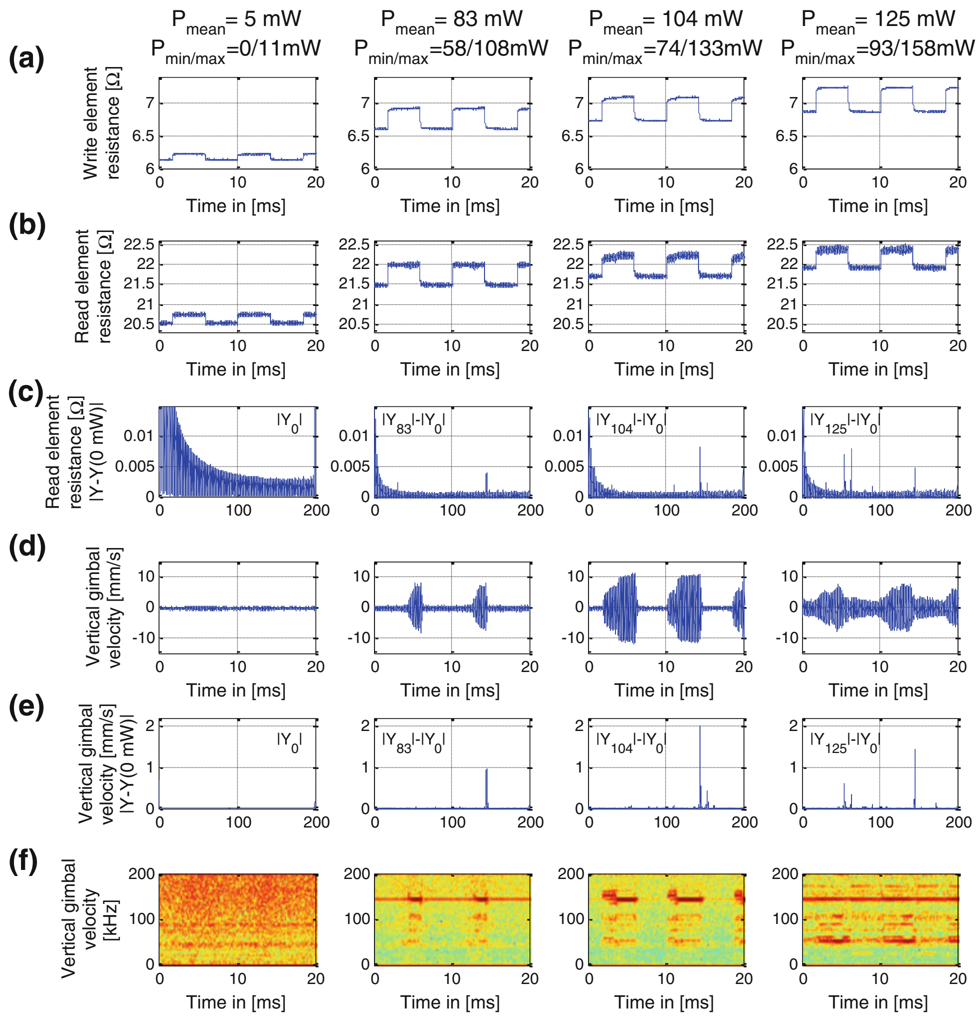

Fig. 4 **a** Write element resistance, **b** read element resistance, **c** change in frequency spectrum of the read element resistance after subtracting the resistance spectrum $|Y_0|$ at 5 mW, **d** vertical gimbal velocity, **e** change in frequency spectrum of the vertical gimbal velocity after subtracting the resistance spectrum $|Y_0|$ at 5 mW and **f** time frequency plot of the gimbal velocity for a square wave heater input of 5 mW (*1st column*), 83 mW (*2nd column*), 104 mW (*3rd column*) and 125 mW (*last column*)

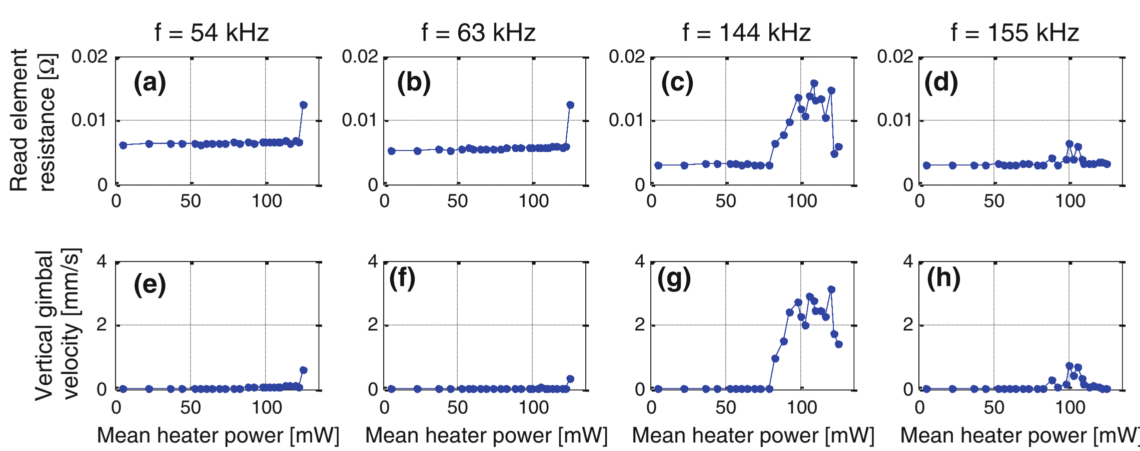

Fig. 5 Amplitude of frequencies at 55, 63, 144 and 155 kHz as a function of heater power for a square wave heater input profile

shows that a frequency at 144 kHz appears in the amplitude spectrum of the read element resistance for a heater power larger than 79 mW. This frequency decreases in amplitude for a heater input above 113 mW. From Fig. 5d we observe that a new peak at 155 kHz appears in the resistance of the read head for a mean heater power between 79 and 122 mW. The second row of Fig. 5 shows that the same frequencies occur in the LDV measurement of the vertical gimbal velocity for the same range of heater power as observed for the read head resistance. Again, this correlation of frequencies in the resistance and velocity spectrum leads us to the conjecture that the increase of the read head resistance is related to frictional heating due to slider-disk contact.

3.2 Temperature calibration measurement

Figure 6 shows the resistance change of the read and write element as a function of temperature. The resistance changes are normalized by the initial resistance of 20.9 Ω for the read element and 6.1 Ω for the write element, respectively, measured at 25 °C room temperature.

We observe from Fig. 6, that a linear relationship exists between resistance change and temperature for both the read and write element. Furthermore, we observe that the resistance change in percent is larger for the write element than the read element. This is related to the different material properties of the read and write element.

3.3 Read element resistance and temperature increase for unloaded, loaded and flying slider

Prior to determining the temperature rise at the read element from resistance measurements, we have studied the resistance change of the read element as a function of heater power for the following three cases: (a) the slider is removed from the disk, (b) the slider is loaded on a stationary disk and (c) the slider is flying over the disk. The results for these resistance measurements are shown in Fig. 7.

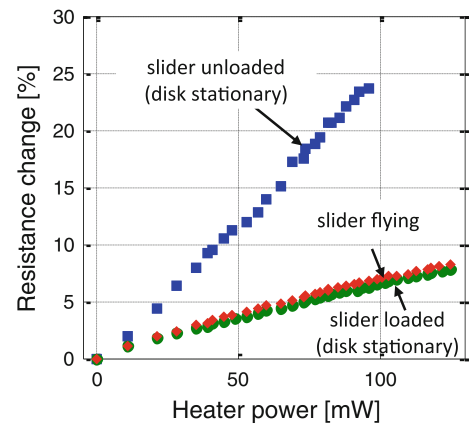

Fig. 7 Resistance change of the read element as a function of heater power for **a** unloaded slider, **b** loaded slider on a stationary disk and **c** flying slider

From Fig. 7 we observe that the resistance change in percent is largest for the unloaded slider case, when the slider is removed from the disk. The resistance of the read element increases nearly linearly as a function of heater power. If the slider is loaded against the stationary disk or is flying over the rotating disk, the resistance increase is substantially less than for the unloaded case. If the slider is removed from the disk (unloaded case), a major part of the heat generated by the heater element is conducted through the slider body to the read element. This temperature increase results in a resistance increase of the read element. If the slider is in contact with the stationary disk or flies over the disk, the slider is cooled by the disk or the air bearing, respectively. Thus, the resistance increase of the flying slider is smaller than for the unloaded slider. From

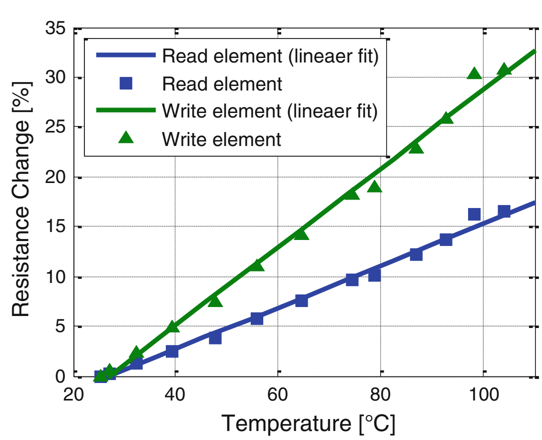

Fig. 6 Resistance change of the read and write element as a function of temperature

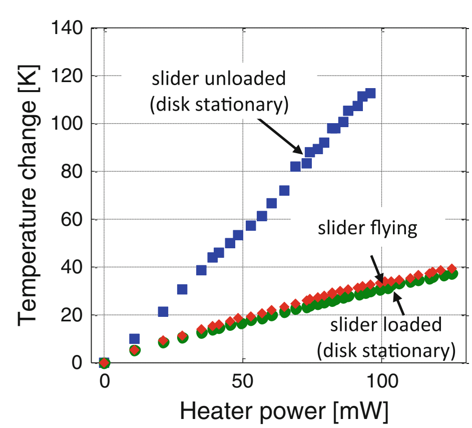

Fig. 8 Temperature change of the read element as a function of heater power for **a** unloaded slider, **b** loaded slider on a stationary disk and **c** flying slider

the results of Fig. 7 we conclude that the cooling effect due to the air bearing and due to heat conduction into the disk is on the same order.

Figure 8 shows the estimated temperature change of the read element for the unloaded, loaded and flying slider case. The temperature change of the read element was obtained by dividing the normalized resistance change measurements shown in Fig. 7 by the results from Fig. 6. As shown in Fig. 8, the temperature increases 115 K at the read element for the unloaded case if the heater is energized to 95 mW. If the slider is loaded onto the stationary disk, the disk acts as a heat sink and the temperature increases only about 38 K. During flying, the slider is cooled by the air bearing and the resistance of the read element increases by 39 K.

3.4 Temperature rise for a constant and a square wave heater input profile

3.4.1 Temperature increase for a constant heater input profile

In Fig. 9, the maximum temperature rise at the read element during stable flying conditions is plotted as a function of heater power for a constant heater input profile.

As presented earlier, for a heater power below 99 mW, the slider was flying stably, i.e., the temperature increase at the read element was entirely caused by heat dissipation due to energizing the heater. For a heater power above 99 mW, an increase in the LDV measurement of the vertical gimbal velocity was detected, i.e., the slider was contacting the disk. If the slider makes contact with the disk, the temperature increase at the read element is caused not only by energy dissipated in the heater, but also by frictional heating during slider-disk contact. In order to estimate the temperature increase due to frictional heating during slider-disk contacts,

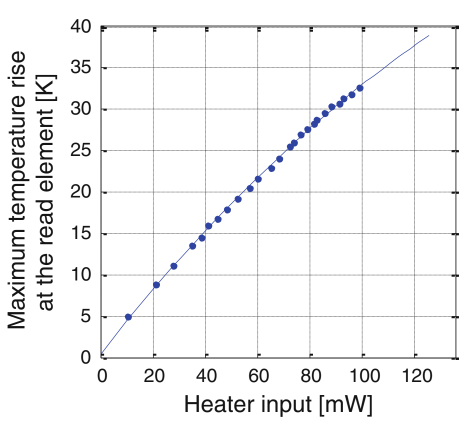

Fig. 9 Estimated temperature at the read element as a function of heater power when the slider was flying stably

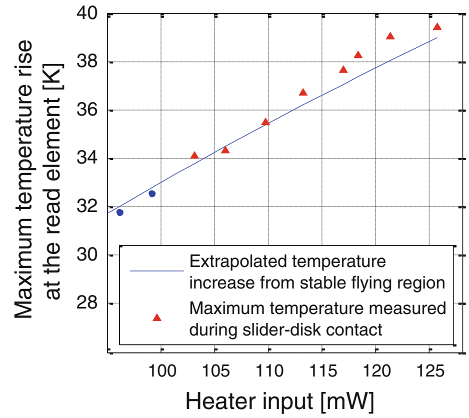

Fig. 10 Maximum temperatures measured during slider-disk contact and extrapolated temperature increase from the stable flying region below 103 mW to the unstable flying region above 99 mW for a constant heater input profile

we proceeded as follows: We first extrapolated the temperature increase from the stable flying region to the unstable flying region ($P > 99$ mW) using a second order polynomial curve fit. The temperature increase obtained using this procedure can be assumed to correspond to the temperature increase caused by heat dissipation from the heater only. We then compared the extrapolated temperature increase to the actual measured temperatures that were obtained when the slider was contacting the disk, i.e., when heat dissipation and frictional heating effects were present. The difference between the extrapolated curve and the actual measurements represents an estimate of the temperature increase due to frictional heating (Fig. 10).

From Fig. 10 we observe that the temperature increase due to frictional heating that is measured by the read element is only on the order of 1 or 2 K. In other words, the temperatures measured by the read element are only slightly larger than the extrapolated temperature increase without slider-disk contact. Therefore, we conclude that the temperature change at the read element is mainly caused by Joule heating due to the heater element and not by frictional heating. Clearly, flash temperatures are not measurable using the resistance change of the read element.

3.5 Temperature increase for a square wave heater input profile

The same procedure of the previous section for estimating the temperature increase due to frictional heating was applied to the experiments with the square wave heater input profile (Fig. 11). From Fig. 11 we observe that the temperature increase at the read element due to frictional heating during slider-disk contacts is again only one or two degrees Kelvin. This value is far below the expected flash temperatures that occur during slider-disk contacts. Thus,

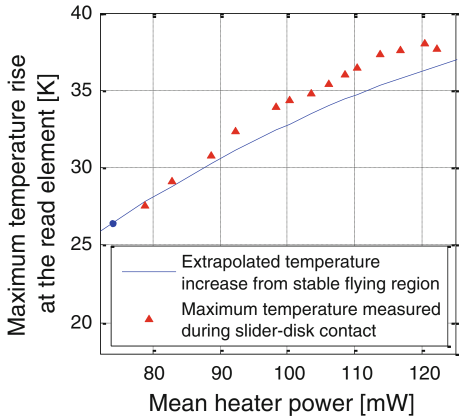

Fig. 11 Maximum temperatures measured during slider-disk contact and extrapolated temperature increase from the stable flying region below 74 mW to the unstable flying region above 74 mW for a square heater input profile

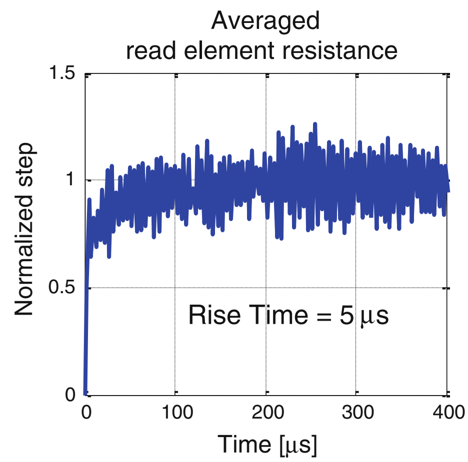

Fig. 12 Averaged normalized response time of the read element for a square wave heater input with a step size of 1 V

we conclude again that flash temperatures cannot be obtained from the resistance change at the read element.

4 Discussion

Comparing Figs. 3 and 5, we observe that the gimbal is excited at only one frequency in the case of a constant heater input profile while additional frequencies are excited for a square wave heater input profile. In particular, we observe that the gimbal is excited at 144 kHz for a constant heater input profile if the power input to the heater exceeds a critical level. On the other hand, for a square wave input profile the gimbal exhibits vibrations at 54, 63, 144 and 155 kHz. In addition, we observe from Figs. 3 and 5 that the critical heater power that results in vertical gimbal vibrations at 144 kHz is smaller for a square wave profile than for a constant heater input. This is apparently related to the time dependent changes in the heater power input. Further investigations of this effect are desirable since time-dependent heater input power changes will be needed for active flying height control of TFC sliders (Boettcher et al. 2011).

In our experiments, we did not observe a sharp resistance increase at the read or write element that could indicate the occurrence of so-called flash temperatures. There are several reasons why flash temperatures could not be observed experimentally using the resistance change of the read or the write element. First, at high disk speeds, flash temperatures occur only for very short time duration on the order of nano-seconds. Since the read element has a limited response time, the detection of very short temperature spikes is limited. In fact, the data obtained in this paper correspond to low-pass filtered data where the cut-off frequency of the filter is given by the time constant of the read element. Figure 12 shows the averaged normalized response time of the read element for a square wave heater input with a positive step of 1 V. Here, we define a positive step as a step to a higher heater input power level. We observe from Fig. 12 that the time constant of the read element is on the order of 5 µs. This time constant is too large to capture a short temperature rise in the nano second range. The actual response time of the read element is likely to be shorter if the read element would be heated directly. Secondly, it is apparent that flash temperatures occur at the peaks of contacting asperities. Thus, the area over which flash temperatures are present is a very small area (Ray and Chowdhury 2007). If the read element is not exactly at the position where contact occurs, the read element "sees" a smaller increase in temperature compared to the temperature rise at the contact spot. Thus, in addition to the time resolution issue of the read element there is a spatial resolution issue related to the spatial separation between the read element and the location of contact.

An approximate expression for the temperature decay over time and space for an instantaneous heat source was presented by Carslaw and Jaeger (1947) who treated the case of a finite amount of heat Q being liberated over a vanishingly small volume at position (x', y', z') at time $t = 0$. They showed that the temperature T as a function of time t and distance r to the heat source can be expressed as

$$T(r,t) = \frac{Q}{8(\pi\kappa t)^{3/2}} e^{\left(-\frac{r^2}{4\kappa t}\right)} \tag{1}$$

where λ is defined as

$$\lambda = \frac{k}{\varrho c} \tag{2}$$

with k representing the thermal conductivity, ϱ the density and c the specific heat of the substrate. It can be seen from

Eq. (1) that the temperature decays quickly with time and distance from the heat source. Thus, the resistance change at the read element cannot be used for estimating the interfacial temperature rise if the contact spot is not exactly at the position of the read element or if the time response of the read element is longer than the flash temperature rise at the contact spot. Furthermore, it is likely that the volume of the contacting asperities at which flash temperatures occur is much smaller compared to the volume of the read element. Therefore, the thermal energy that is generated when flash temperatures occur is most likely too small to cause a sufficiently large response of the read element.

5 Conclusions

Experiments have been performed to investigate contacts and temperature changes between a TFC slider and a magnetic disk. To achieve contacts, the heater element of a TFC slider was energized with constant and square wave input profiles with increasing bias. To estimate the temperature rise during contacts, auxiliary resistance calibration measurements were carried out in a temperature controlled environment. Using this relationship we estimated the temperature rise at the read and write element as a function of heater power.

We conclude that

- Slider disk contacts and vertical gimbal vibrations are detected by LDV measurements if the heater input exceeds a critical level.
- For a square wave heater input profile, gimbal vibrations at 144 kHz were observed for a smaller heater power compared to a constant heater input profile; furthermore, it was found that additional frequencies were excited compared to the experiment with a constant heater input profile.
- The resistance of the read and write element increases as a function of temperature. The temperature rise at the read element is mainly caused by power dissipation in the heater of the TFC slider.
- The resistance change at the read element cannot be used to estimate the interfacial temperature rise due to frictional heating during contact. Reasons are the limited time response of the read element and the spatial separation between the contact spot and the read element. In addition, the thermal energy at contacting asperities is too small to cause a sufficiently strong response of the read element.

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