Slider Dynamics in the Lubricant-Contact Regime

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Abstract

Thermal Fly-height Control sliders that are capable of sub-nanometer level actuation are used to investigate the vertical, down-track and off-track slider dynamics in slider-disc lubricant contact. Slider-lubricant contact introduces significant excitation in all three directions, and the slider dynamics is dependent on the degree of lubricant-contact. The lubricant surface has a significant role in determining the physical clearance and slider fly-height. While slider-lubricant contact may be successfully achieved by carefully controlling the heater power, improved slider designs and associated heater induced protrusion profiles are necessary to successfully mitigate contact induced vibrations and meet the challenges for future hard disc drives.

I. INTRODUCTION

The disc drive industry’s density target of 10 Tb/in^2 in hard disc drives (HDD) within the next decade requires a significant change in head-disc interface and likely involves a combination of new technologies such as Heat Assisted Magnetic Recording (HAMR), Bit Patterned Media Recording (BPMR) and Two-dimensional Magnetic Recording (TDMR) to mention a few. Independent of the actual recording technology, it is necessary to reduce the magnetic spacing to within 2nm, which implies a physical spacing of 0.25nm at the read-write transducer location. At such a small spacing intermittent contact between the slider and the lubricant layer or hard overcoat surface on the disc becomes inevitable. A continuous lubricant-contact HDI may in fact be necessary to meet future magnetic spacing needs. While the new recording technologies impose a significantly tighter budget on the slider dynamics in all three directions (vertical, down-track and off-track), the contacting HDI must be reliable ensuring no degradation of lubricant or disc overcoats even after prolonged operation.

The effect of contact on slider vibration has received much attention because of its detrimental effect on magnetic read-write as well as servo performance and abundant literature exists on this topic. On the experimental side, traditional sliders were brought into the near-contact and contact regime by lowering the disc RPM, and the ensuing slider vibrations were investigated using various techniques [1-4]. Slider dynamics resulting from stronger lubricant-slider interactions at small spacing were also studied [5-7]. Simulation studies focused on developing accurate models to predict slider flying instabilities and slider-disc contact [8, 9]. With the goal of meeting future spacing needs, a partial-contact HDI system was explored. It was shown through experiments and simulations that a small contact area and low contact/friction forces at the HDI are necessary to have low vibration and good wear performance [10-12]. The current slider technology uses Thermal Fly-height Control (TFC) capability to bring the read-write portion of the slider closer to the disc by resistive heating induced thermal deformation. While sub-nanometer level clearance can be achieved using the TFC, slider stability and HDI reliability at very small spacing remains to be understood. In order to further reduce the magnetic spacing using the TFC architecture, a recording strategy with a small portion of the TFC protrusion in intermittent or continuous contact with the lubricant layer of the disc has been proposed [13]. However, there is limited theoretical and experimental work to verify the feasibility of this technique [14, 15].

In this paper TFC sliders which are capable of sub-nanometer level actuation are used to experimentally investigate the 3D slider dynamics when actuated into contact with the lubricant layer on the disc. The results of this investigation show that slider-lubricant contact may be successfully achieved by carefully controlling the heater power. The lubricant surface plays an important role in determining the physical clearance and slider fly-height, and the slider dynamics is dependent on the extent of slider-lubricant contact.

II. EXPERIMENTS

The experiments are performed with ‘pemto’ TFC sliders (1.25mm x 0.84mm) on a 95mm media coated with 13Å PFPE lubricant (60% bonded ratio). Slider vibration is measured using Laser Doppler Vibrometer (LDV), contact at the HDI is monitored using an Acoustic Emission (AE) sensor, and lubricant profile changes are measured using an in-situ Optical Surface Analyzer (OSA) (Fig 1). Power to the slider's heater is supplied using a data acquisition board and amplifier circuit controlled using custom built Labview code. The power input system offers the flexibility of supplying programmable waveforms together with sub-milliwatt power resolution. Touchdown power (TDP) is measured by an automated program that gradually increases the heater power using AE signal as feedback. The power corresponding to a sudden jump in AE signal is defined as the TDP, and the heater power is automatically turned off upon touchdown detection (Fig 2a). The difference in the lubricant profile after and before the test shows changes at discrete locations under the protruded center-pad and sometimes under the side-pad (owing to slider roll) where slider-lubricant contact occurs (Fig 2b).

A. Establishing slider-lubricant contact

Since the objective of this work is to investigate slider dynamics in contact with the lubricant, experiments are first conducted on a partly delubed disc to establish slider-lubricant contact. Delubing is performed by immersing part of the disc in a HFE solution for 10 minutes. The section of the disc immersed in HFE is stripped of the 'mobile' and some 'bonded' lubricant and left only with a 'bonded' lubricant layer. Therefore, it has a lower lubricant thickness than the lubed section. Assuming 50% lubricant removal, the thickness difference between the lubed and delubed sections would be about 6.5 Å. In this work, results are reported for a slider flown over a test track that has 75% lubed and 25% delubed sections.

The experimental procedure is as follows: The slider is loaded and flown passively (no heater power) for 20 minutes on the experimental track. The TDP is measured. The slider is then subject to an input power profile (Fig 3a) with a dwell time of 5 seconds at the maximum power. The maximum power is varied from 0.8TDP to 1.3TDP in steps of 2.5mW, and the slider's vertical velocity is captured at 1MHz sampling rate. OSA scans of the disc surface before and after the test are used to monitor the change in lubricant profile. All tests are performed at 0^o skew and design linear velocity of 22 m/s unless mentioned otherwise.

B. Slider dynamics under lubricant-contact

Once the conditions that correspond to slider-lubricant contact are established, detailed investigations are carried out to understand the effect of lubricant contact on the three dimensional slider dynamics (vertical, down-track and off-track) by flying the slider on a fully lubed disc. For simplicity, the directions normal to the slider faces are referred to as the down-track and off-track directions, even for non-zero skew. The power profile (Fig 3b) input to the heater for these investigations consist of four cycles of a sine waveform with a time period of two seconds.

III. RESULTS AND DISCUSSION

A. Establishing slider-lubricant contact

The touchdown power for the experiments on partly delubed disc was determined to be 77mW. When the heater maximum power is 3mW above TDP (Fig 3a), the slider contacts only the lubed section of the disc (Fig 4a). As shown in the schematic (Fig 5), such a condition reflects contact with only the mobile lubricant. Tests for repeatability confirm that such a condition of contact with only the mobile lubricant layer can be established when the heater power is slightly above the TDP.

This experiment shows that the slider flies with a lower clearance from the lubricant top surface in the lubed section of the disc compared to the top surface in the delubed section of the disc (Fig 5). This decrease in clearance may be attributed to molecular non-uniformity/rough nature of the mobile lubricant layer in the lubed section. For a slider flying at a given clearance from the mean lubricant surface, the extended backbones of the mobile lubricant or areas of thicker lubricant films can come into strong interaction/contact with the slider if the non-uniformity/roughness is sufficiently large. Based on the experimental observations, it is inferred that the lubricant non-uniformity/roughness (or viewed differently, the glide height) of the mobile lubricant (lubed section) is higher than that for the bonded lubricant (delubed section), and hence the clearance is lower in the lubed section.

Interestingly, based on surface energy arguments, lubricant non-uniformity/roughness should lead to a reduction in clearance. It is well known that the disc surface energy is strongly influenced by the thickness of the lubricant (the dispersive part varies inversely as the square of the lubricant thickness; the polar part has a different dependence on lubricant thickness [16, 17]). Therefore, the total surface energy of a non-uniform lubricant film averaged over an area will be greater compared to that for a uniform lubricant film of the same mean thickness, and this increase in surface energy, in effect, tends to reduce the clearance. It is envisioned that deliberate patterning/roughening of the lubricant may be used to reduce the clearance, provided the patterning/roughening is chosen optimally to avoid enhanced slider-lubricant interactions at the thickest lubricant areas and the reliability of the HDI can be ensured.

When the heater power is increased to 13mW above TDP, slider contact is established with the lubed and delubed sections of the disc (Fig 6). Contact with the delubed section is assumed to be contact with only the bonded lubricant, while contact in the lubed section at this power is contact with the top mobile plus underlying bonded lubricant layer.

The change in slider dynamics during lubricant contact is indicated by the spectrum of the slider's vertical velocity. When flying without contact (no heater power, Fig 7a) the slider's vertical velocity is not excited at any specific frequency. Contact with only the mobile lubricant causes slider excitation at 129kHz (Fig 7b), presumed to be the first pitch mode. A significant change in the slider's vertical dynamics occurs when contact is established with the bonded lubricant (Fig 7c) with the slider's excitation shifting to 231kHz, presumed to be another dominant vibration mode for this slider. The presence of the mobile lubricant does not have a significant influence on the slider's dynamics when contact is established with the bonded lubricant layer (Fig 7c,d).

Based on these results it is concluded that at the onset of lubricant-contact, the slider is excited at the first pitch mode (129kHz). A stronger lubricant-contact condition excites the slider at its dominant secondary mode (231-233kHz). These excitation frequencies are observed for this slider design in experiments conducted at differing disc rotation speeds implying that the slider responds at its natural modes, determined by the air-bearing and suspension stiffness, and not at any forced excitation frequencies within the system, such as those from disc waviness/roughness.

B. Contact loss above a critical power beyond TDP

For this particular slider design, when the heater power is increased well beyond the TDP, the AE signal is suddenly suppressed (Fig 8c) indicating a possible loss of contact (or reduction in contact intensity) above a critical power. This phenomenon is repeatable for this slider design when experiments are performed over different media. It is speculated that this condition corresponds to the case of lube-surfing, where only a part of the TFC protrusion is in contact with the lubricant, and the slider's dynamics as well as AE signal are damped out by the lubricant [13]. Another distinct possibility is that the air-bearing pressure due to TFC protrusion is altered in a way that makes it able to support the slider and it flies at a secondary stable fly-height without lubricant-contact.

Analysis of the slider's vertical dynamics (Fig 8b) shows that the vertical velocity spectrum at higher heater power (Fig 8d) is similar to that for passive flying (Fig 7a), except for small changes around 270kHz. In addition, OSA scans reveal that while there is a significant change in the lubricant profile when the maximum power is below the critical power (Fig 9a,b), the change is insignificant when the heater power is above the critical power (Fig 9c). The evidence from slider vertical dynamics combined with the lack of lubricant profile changes at higher heater power support the argument that when the heater power is increased beyond a critical power, the slider's attitude may adjust so as to achieve a stable flying condition with no contact.

It is pointed out that such a loss of contact above a critical power is a slider design specific phenomenon. The 3σ of AE signal and vertical velocity are plotted for a slider design that shows no loss of contact when the heater power is increased to 30% above the TDP (Fig 10a). A similar plot for the 'pemto' slider considered in this work shows loss of contact above a critical power (Fig 10b). It is also noted that slider stability and HDI reliability for prolonged flying at high heater powers requires further investigation. Preliminary experiments show that when the slider is flown at higher heater power for 5min, the high pressure under the TFC protrusion creates a lubricant depletion track superposed with lubricant rippling at the ABS frequencies even when the AE signal remains suppressed (Fig 11c). Such a lubricant profile change under the TFC protrusion may excite slider dynamics and eventually lead to slider instability, contact and HDI failure [5, 7].

C. 3D slider dynamics under lubricant-contact

The three dimensional slider dynamics under lubricant-contact are measured by conducting experiments on fully lubed disc. The 3σ of the vertical, down-track and off-track velocity signals for the first cycle of the sine waveform (Fig 3b) from experiments conducted at -15^{o} skew and linear velocity of 14.6m/s are shown in Fig 12 together with the AE signal and power profile. The peak power of the sine waveform in these tests is TDP+23mW. These figures confirm the sudden increase in slider excitation during lubricant-contact, and the sudden drop in slider velocity excitation in all three directions when the heater power is above a critical power.

The data in Fig 12 is presented as hysteresis plots for displacements, velocities and AE signal against power in Fig 13. Based on the AE signal data, it is seen that the power required for onset of slider-lubricant contact during the power-up phase (i.e. touchdown power TDP) is 2mW lower than the power at which slider-lubricant contact ceases in the power-down phase (i.e takeoff power TOP). Although not shown here, the TDP and TOP for the remaining three cycles of the sine power waveform are the same as the first, implying that slider or lubricant burnishing is not the cause for the difference in TDP and TOP, and it also requires further investigation. The repeatability of the hysteresis plots for the four cycles adds confidence to the experimental method, in addition to verifying the robustness of the HDI to short duration slider-lubricant contact.

Interestingly, Fig 13 shows that while the slider’s vertical and down-track velocity magnitudes change significantly during contact, the displacement magnitude (computed by integration of the velocity signal) does not show such a stark change. In contrast, however, the off-track displacements show the greatest increase during contact, even though it appears that the off-track velocity is not significantly affected. This behavior may be explained by understanding the dominant frequency content of these signals.

Fig 14 shows the spectrum of the vertical, down-track and off-track velocity for lubricant-contact. Comparing the slider's vertical velocity spectrum Fig 14a to Fig 7, it is inferred that contact with the mobile lubricant occurs at TDP+3mW, contact with the mobile and bonded lubricant occurs at TDP+8mW. While excitation at the ABS related frequencies (129kHz, 234kHz) is seen in all three directions, suspension related frequencies (<50kHz) are seen only in the off-track direction (Fig 14c,d). The contribution to displacement (computed by integrating velocities) is greater from excitation at the lower frequencies than it is from higher frequencies. Since off-track excitation has the lower frequency content from suspension modes, the off-track displacements are significantly larger than the vertical or down-track displacements during lubricant-contact. This result reveals that slider-lubricant contact poses a serious challenge to servo track seek/follow operations.

At TDP+23mW, the heater power is beyond the critical power. It was argued earlier that the slider flies stably without contact at such high heater power. The lack of down-track excitation at high power (Fig 14b) supports this argument because contact events should result in friction forces which are aligned mainly in the down-track direction and thereby excite the slider down-track dynamics significantly.

While the slider may fly without contact at TDP+23mW, its dynamics is slightly different from the passive flying condition (no heater power) as reflected by the presence of vertical excitation at 270kHz (Fig 14a) and off-track excitation at 20kHz (Fig 14d).

IV. CONCLUSION

Slider-lubricant contact is established by carefully controlling the TFC heater power and the three dimensional slider dynamics under lubricant-contact is investigated. Lubricant-contact excites the vertical, down-track and off-track dynamics with greatest displacement change occurring in the off-track direction (for non-zero skew experiments). The degree of slider-lubricant contact determines the slider vibration modes. In general, vertical and down-track dynamics are excited at the ABS frequencies while off-track excitation occurs at ABS as well as suspension frequencies. For specific slider designs, there is a sudden drop in AE signal and slider excitation when the heater power is increased above a critical power (beyond TDP). This phenomenon has been speculated to be the lube-surfing regime, but the evidence in this work points to the contrary: the slider appears to attain a secondary (stable) flying state without any lubricant-contact and requires further investigation. The lubricant surface non-uniformity/roughness may have a significant influence on the physical clearance and the slider fly-height similar in fashion to the slider-disc roughness. Deliberate 'patterning' of the lubricant is envisioned as a novel technique to reduce slider clearance and fly-height.

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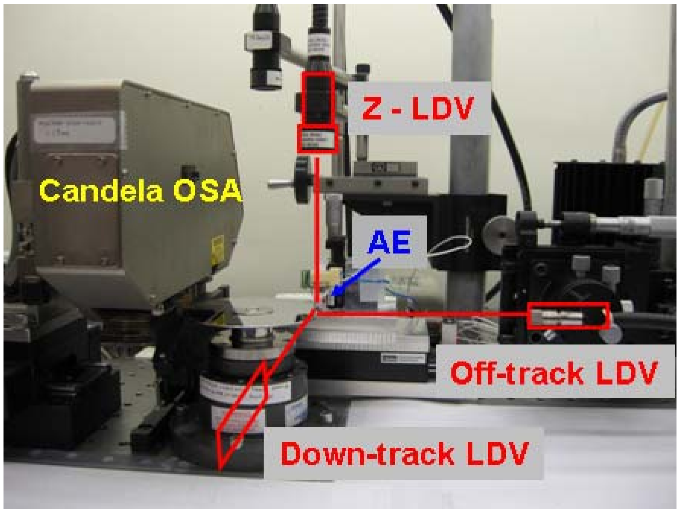

Fig 1 Experimental set-up

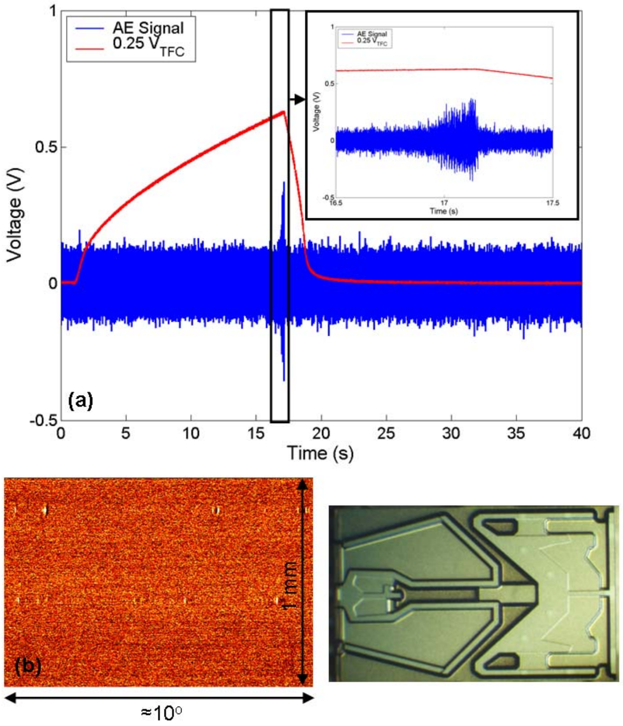

Fig 2 Touchdown detection test (a) AE signal (b) Lubricant profile change

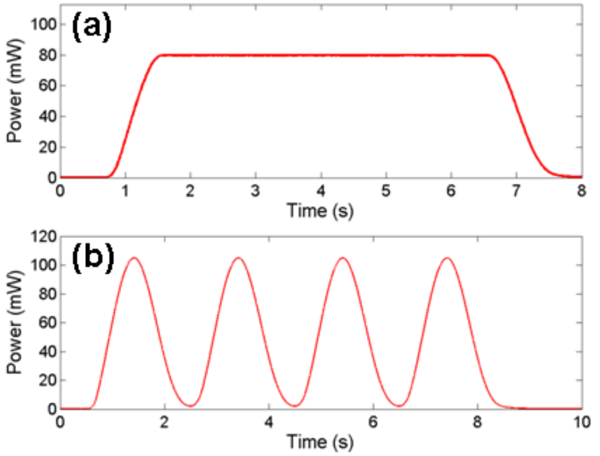

Fig 3 Power input profile for (a) establishing slider-lubricant contact (b) slider dynamics investigations

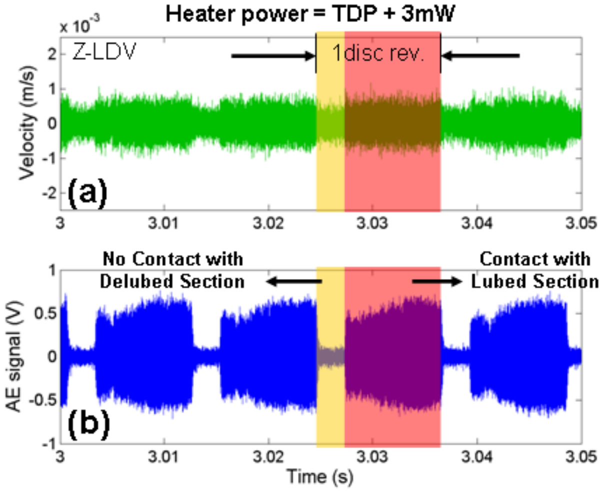

Fig 4 Contact with lubed section (a) slider's vertical velocity (b) AE signal

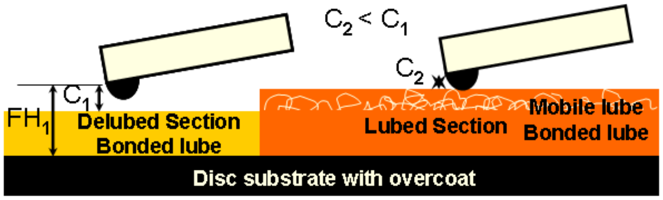

Fig 5 Schematic: Clearance loss in the lubed section

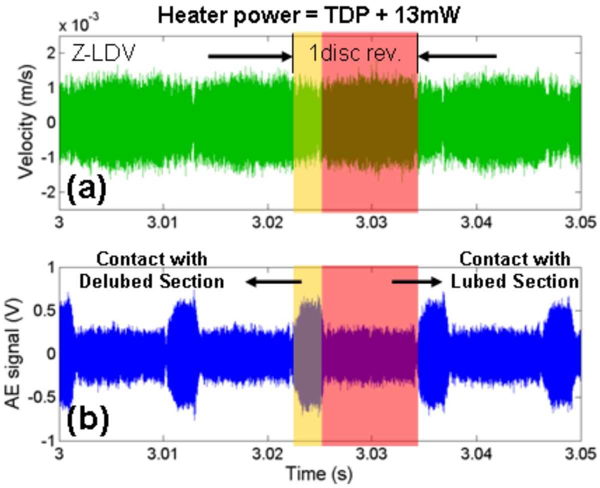

Fig 6 Contact with lubed and delubed sections (a) slider’s vertical velocity (b) AE signal

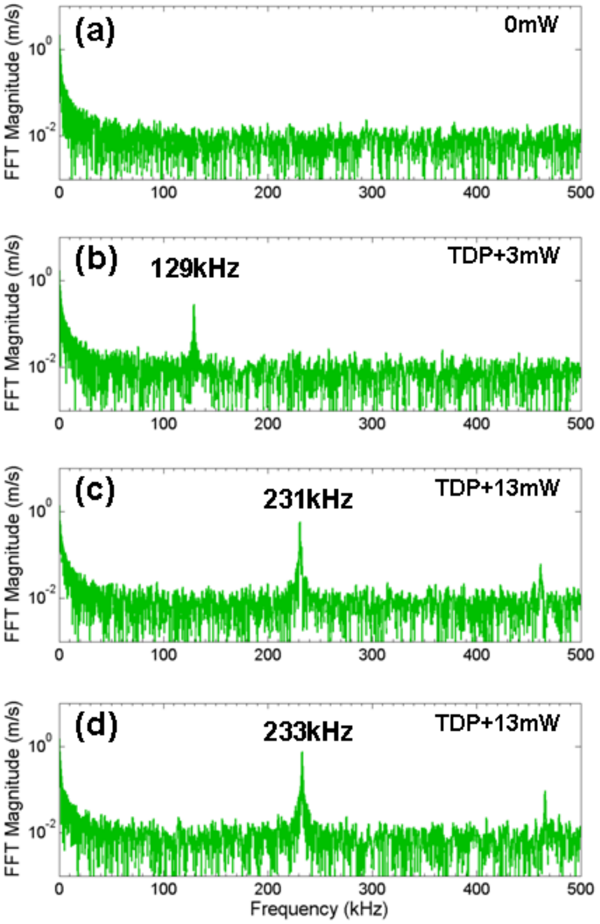

Fig 7 Spectrum of slider’s vertical velocity (a) passive flying (no heater power) (b) contact with mobile lube (c) contact with bonded lube (d) contact with mobile and bonded lube

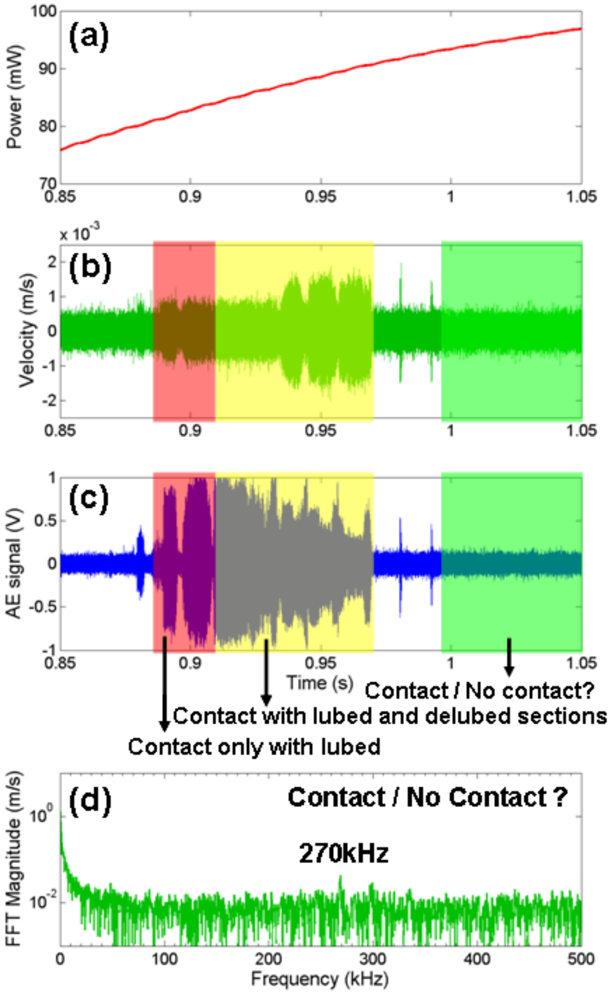

Fig 8 Possible contact loss at higher power (a) power (b) slider's vertical velocity (c) AE signal (d) vertical velocity spectrum

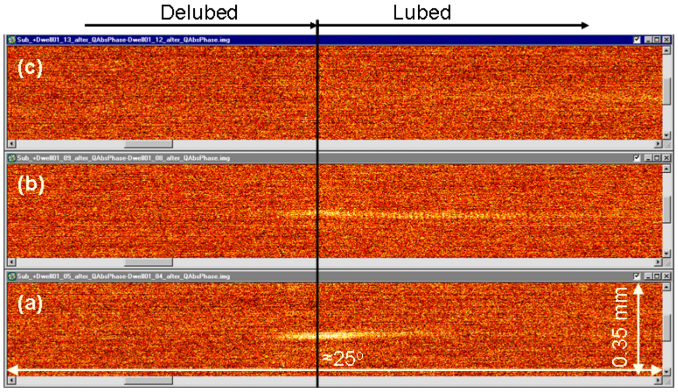

Fig 9 Lubricant profile change after 5 sec. (partly delubed disc) (a) TDP+3mW (b)TDP+13mW (c) TDP+23mW

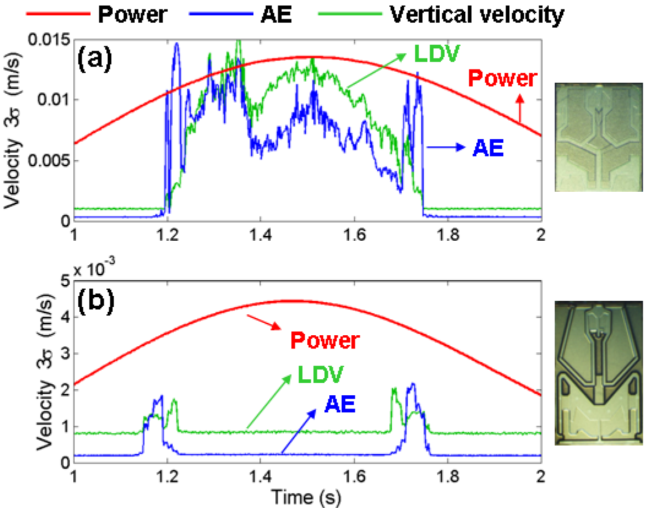

Fig 10 Response at high heater power (max power = 1.3 TDP) is slider design dependent (a) no loss of contact (b) loss of contact above a critical power

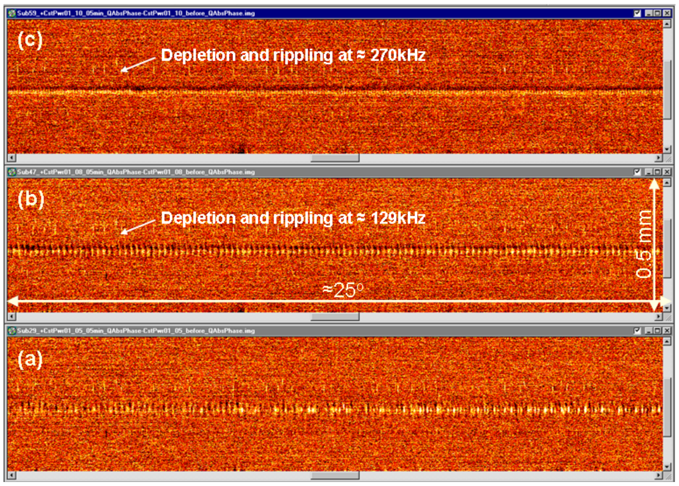

Fig 11 Lubricant profile change after 5min. (fully lubed disc) (a) TDP+2mW: contact with mobile lube (b) TDP+13mW: contact with mobile and bonded lube (c) TDP+25mW: above critical power with suppressed AE signal

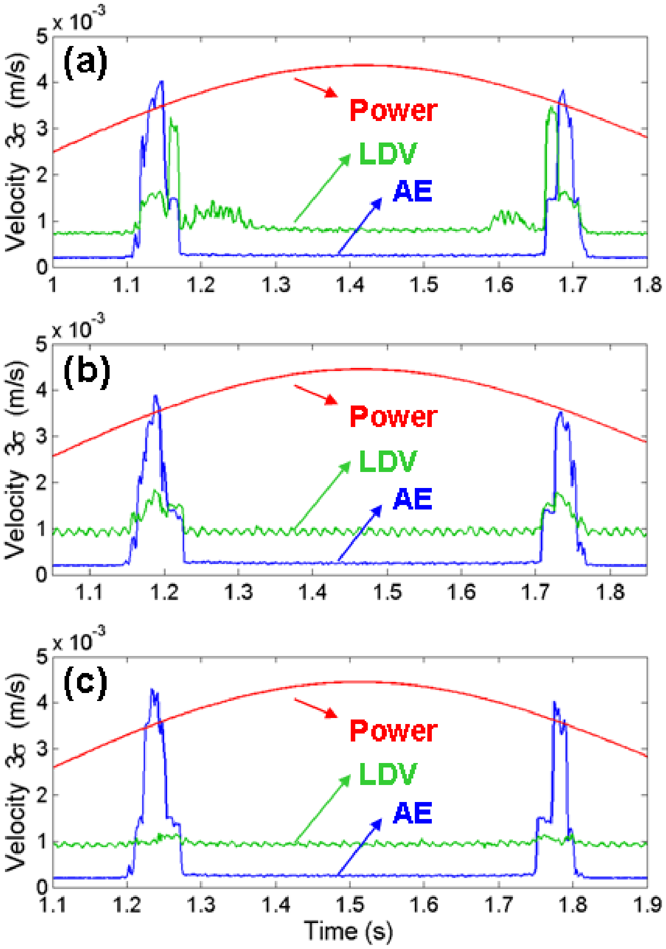

Fig 12 Time history of heater power, 3σ of AE signal and 3σ of velocity signal (a) vertical (b) down-track (c) off-track

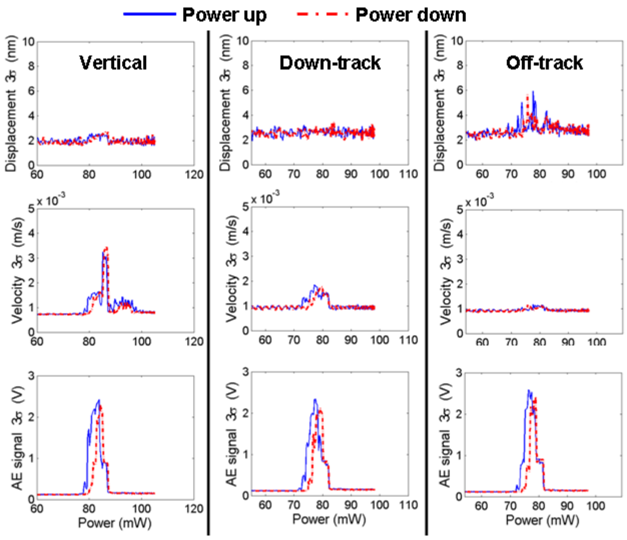

Fig 13 Hysteresis plots against power (maximum power is TDP+23mW). First row: displacement; second row: velocity; third row: AE signal.

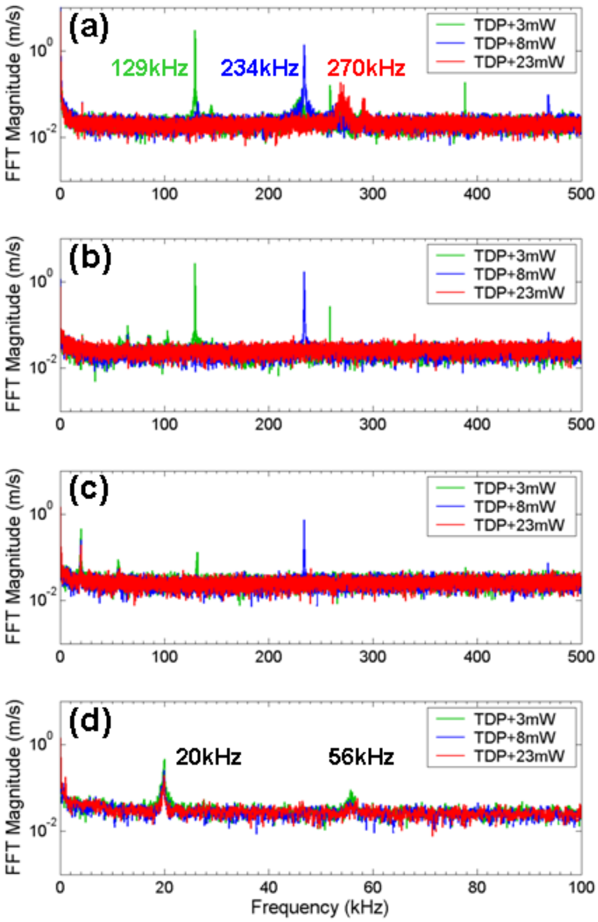

Fig 14 Frequency spectrum for transient tests at -15^o skew (a) vertical (b) down-track (c) off-track (d) off-track zoomed