Parametric Investigations at the Head Disk Interface of Thermal Fly-height Control Sliders in Contact

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Abstract

Accurate touchdown power (TDP) detection is a pre-requisite for read-write head to disk spacing calibration and control in current hard-disk drives (HDD), which use the thermal fly-height control (TFC) slider technology. The slider air bearing surface (ABS) and head gimbal assembly (HGA) design have a significant influence on the touchdown behavior and this paper reports experimental findings to help understand the touchdown process. The dominant modes/frequencies of excitation at touchdown can be significantly different leading to very different touchdown signatures. The pressure under the slider at touchdown and hence the TFC efficiency as well as the propensity for lubricant pick-up show correlation with touchdown behavior that may be used as metrics for designing sliders with good touchdown behavior. Experiments are deviced to measure friction at the head disk interface (HDI) of a TFC slider actuated into contact. Parametric investigations are conducted to study the effect of disk roughness, disk lubricant parameters and the ABS design on the friction at the HDI as well as slider burnishing/wear and reported.

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I. INTRODUCTION

In order to realize higher magnetic storage densities in hard disk drives, it is necessary to reduce and control the read-write head to media spacing, or equivalently, the physical spacing/clearance separating the head from the disk. Current HDD products operate with sub-nanometer clearances using the thermal fly-height control (TFC) technology; where the TFC heater locally deforms the region around the read-write head of the slider bringing it closer to the disk. The head to disk clearance can therefore be adjusted by changing the power supplied to the TFC heater.

A touchdown test is used to calibrate the TFC heater power to the clearance. The heater power required to make the head contact the disk lubricant surface i.e. the touchdown power (TDP) is first determined, and the heater power is then reduced to retract the head away from the disk in order to achieve a target clearance. Accurate TDP detection is therefore a key enabling step to using the TFC technology. Inaccurate TDP detection can severely compromise the drive performance: if the actual clearance is too high, the recording performance suffers, and if the actual clearance is too low, it increases the probability for head-disk contact, which leads to unwanted head wear, thus compromising drive reliability.

Research studies on the slider-disk contact interactions and the resulting slider vibrations have been of interest to the hard disk drive (HDD) community for a long time. Research investigations on the traditional (non-TFC) slider dynamics were motivated by the need to design low flying sliders while mitigating the contact induced slider vibrations and slider-lubricant interactions, and extensive literature exists on these topics [1–8]. After the introduction of TFC sliders, several researchers have tried to understand and explain the contact and touchdown behavior of TFC sliders owing to its importance in HDD spacing calibration. It has been shown through experiments and simulation that in addition to the slider air bearing surface (ABS) design, the disk lubricant and suspension design play an important role in the slider touchdown process [9]. Numerical simulations accounting for the nonlinear forces at the head-disk interface (HDI) have also successfully explained the strong vibration dynamics of the slider close to the TDP and the subsequent suppression of vibrations for powers higher than the TDP [10, 11], and these results qualitatively agree with the experimental results observed for certain ABS designs [12, 13]. A full understanding of the touchdown behavior of TFC sliders is still lacking, and it continues to be an active topic of research.

In this work, Acoustic emission (AE) sensors and laser doppler vibrometers (LDV), are used in spinstand experiments focussed on touchdown detection and slider dynamics studies. The similarities and differences in touchdown signature for different slider ABS designs are highlighted. Parametric investigations are conducted to explain the dependence of friction and head wear on disk roughness and lubrication condition. In conjunction with recent work on the interactions of TFC sliders with the disk lubricant during touchdown/contact [14, 15], these results help develop a better understanding of the touchdown process of TFC sliders and the complex interactions at the HDI.

II. EXPERIMENTS

Experiments are conducted using three different ABS designs mounted on the same suspension on a spin stand equipped with an AE sensor to detect contact and an LDV to detect vertical flexure motions on the head gimbal assembly. The TDP (i.e. power required to achieve zero clearance or contact with the disk lubricant) is determined experimentally by supplying the TFC heater with a square pulse lasting $70ms$ with increasing power. The AE signal standard deviation is monitored during each power pulse, and the power at which the AE signal standard deviation crosses a specified threshold (set to be 20% above baseline) is recorded as the TDP.

III. RESULTS AND DISCUSSION

A. Touchdown behavior/characteristics

The touchdown plots for three different ABS designs are shown in Fig 1 where ABS-3 shows a favorable 'sharp touchdown' while ABS-1 shows an unfavorable 'gradual touchdown' with a slow rise in AE signal for increasing TFC power. ABS-2 has touchdown performance which falls between ABS-1 and ABS-3. A sharp touchdown behavior is preferred as it gives a well defined estimate of the exact power at which contact with the disk lubricant is achieved.

The sharp touchdown for ABS-3 is characterized by strong individual spikes in the time history of the AE signal while the gradual touchdown for ABS-1 shows a uniformly increased

AE signal during the TFC pulse as shown in Fig 2. (The AE signal on these plots have been shifted by $1V$ to show them clearly).

In addition, tests in overpush reveal that ABS-3 with 'sharp touchdown' shows an 'overshoot behavior' with very strong AE indicated contact at powers slightly above the TDP and a subsequent suppression of AE indicated contact when the power increases into overpush as seen in Fig 3. In contrast, ABS-1 with the 'gradual touchdown' shows no 'overshoot' behavior but a gradual increase in AE detected contact with overpush. ABS-2 has behavior in between those of ABS-3 and ABS-1.

Simulations for these three ABS designs show that the increasing sharpness of touchdown correlates with decreasing pressure under the TFC protrusion at touchdown, increased TFC efficiency and lower TDP (Table I). It is also observed that lubricant pick-up is higher for ABS-3 compared to ABS-2 or ABS-1.

B. Analogous experimental results

A separate set of experiments with ABS-2 reveals that the touchdown can be sharp or gradual depending on the disk RPM (or the linear velocity) as shown in Fig 4. Specifically, a lower disk RPM increases the touchdown sharpness and a higher disk RPM degrades the touchdown sharpness. It is also observed that the touchdown performance degrades for a burnished slider (which is burnished in a controlled fashion by increasing the TFC power above the TDP on a separate disk track). The results for the 7200 RPM case on Fig 4 highlight the possibility of false TDP detection: for the same 20% AE threshold, the unburnished case shows a gradual AE rise untill about $95mW$, that precedes the sharp AE rise at $102mW$ which actually marks the TDP, however, the burnished case reads a false TDP at $93mW$ owing to the gradual rise in AE that occurs before the sharp AE rise marking touchdown. The time history of the AE signal is similar to that observed with the different ABS designs, namely, strong individual AE spikes appear for the 3600 RPM case with sharp touchdown, and a uniformly increased AE signal appears for the 7200 RPM case with gradual touchdown (Fig 5). These analogous results for ABS-2 provide a way to probe the same HDI under different disk RPM to understand the changes that occur in the AE and LDV signals for 'sharp' and 'gradual' touchdown signatures as well as in overpush (i.e. TFC power above the TDP).

C. LDV spectrum and AE signal content

Experiments are conducted with ABS-2 to simultaneously capture the AE signal and the LDV signal (LDV focused on flexure) to identify the frequencies that correspond to the flexure and slider vertical motions, and to see how they appear in the AE signal. The tests are conducted with the power increased above the TDP (i.e. into overpush). For this ABS-2 design, the simulated air bearing frequencies at 5400 RPM and $1nm$ minimum spacing are $142kHz$ (roll), $167kHz$ (pitch 1) and $324kHz$ (pitch 2).

The LDV spectrum for overpush tests conducted at different RPM are shown in Fig 6, and the dominant excitation frequencies are identified on the plots. It is observed that for 3600 RPM, the lower frequencies (notably 139,148 and $165kHz$ which are close to simulated roll and pitch 1 air bearing frequencies) are dominant, while for the 7200 RPM, the higher air bearing frequency $321kHz$ (corresponding to pitch 2 air bearing frequency) is dominant. This result indicates that the mechanism/nature of touchdown and contact at the HDI is significantly altered by the disk RPM, and it is probably different for the three different ABS designs presented in section III A in an analogous fashion.

The components of the AE signal at the different frequencies observed in the LDV signal are plotted in Fig 7 to observe how they change as a function of the TFC power. (The cumulative effect of adding all these components would result in the plot shown in Fig 4). At 3600 RPM the touchdown is marked by the sharp rise in the $148kHz$ component and there are no components that show gradual rise. At 5400 RPM, the $148kHz$ component shows a gradual rise, but touchdown is marked by a sharp rise in the $321kHz$ component. At 7200 RPM, there are no components with a sharp rise, and the $321kHz$ component shows a gradual rise.

These results indicate that at 3600 RPM the contact is dominated by the slider's pitch 1 and roll motions (together with any suspension related motions that give rise to frequency peaks in the $65 - 100kHz$ region.) At 7200 RPM, contact is mainly dominated by the vibration of the slider at the pitch 2 frequency. At 5400 RPM, the contact interaction is a combination of the above two modes at lower TFC powers causing a gradual rise, first in the $148kHz$ component, but eventually touchdown causes a strong vibration in the pitch 2 mode ($321kHz$).

These results are in agreement with recent studies that show that at close spacing and at the onset of lubricant-contact, in-plane shear forces and friction can destabilize the slider for certain ABS designs resulting in vibrations dominantly occurring at suspension and lower air bearing frequencies ($60-200kHz$ in our case) while stronger contact with the disk causes slider vibrations with higher frequency content (above $200kHz$) [9].

D. Friction measurements in contact

Friction forces at the HDI become important during contact conditions and may in fact play a dominant role in HDI performance and slider dynamics. Friction induced slider wear as well as disk lubricant redistribution and disk overcoat damage need to be examined carefully to explore future designs that can accommodate a certain level of head-disk contact.

Experiments are devised to measure the friction forces in the downtrack direction during contact and overpush conditions by instrumenting a strain gage. Once the TDP is determined on the test track, the TFC is powered with a voltage profile having $100ms$ dwell time at the maximum power. It is noted that strain gages have a low bandwidth and several experiments reveal that a dwell time of at least $100ms$ is necessary to allow the strain gage to respond to the friction force and give good, repeatable measurements. All experiments are conducted with ABS-2 on a reference 'standard disk' unless specified otherwise.

1. Friction, AE and slider bouncing in contact

Fig 8a and Fig 8b show the TFC voltage profile and the resulting slider bouncing (displacement and velocity), AE detected contact and the friction force for $10mW$ and $20mW$ overpush, respectively. It is evident that slider bouncing and AE signal remain high throughout the test for $10mW$ overpush and they get suppressed (after an initial overshoot region) for the $20mW$ overpush case. The friction force measured by the strain gage, however, continues to increase with the amount of overpush indicating a higher level of interference and contact for larger overpush powers even though the AE detected contact and slider dynamics get suppressed. (It is noted that the amplitude of the AE signal in the suppressed state is noticeably higher than the baseline AE signal with no TFC power, implying a certain amount of contact).

2. *Effect of disk roughness*

Disk roughness plays an important role in HDI performance. The combined slider and disk roughness affect the nominal physical spacing at the HDI, the magnitude of interaction forces (intermolecular/adhesive etc.) as well as the actual area of contact when it occurs, thereby influencing the magnitude of contact and friction forces. A parametric study is conducted with three disk types: Disk A, B and C with decreasing roughness, in that order, and with surface roughness parameters tabulated in Table II, where, R_q is the root mean square roughness, R_p is the maximum peak height, and R_v is the maximum valley depth.

First, several tests are conducted using the same slider to determine the TDP on a standard disk and on each of the disks A,B and C. Table II presents the change in the TDP (i.e. δTDP) on each of the disks A,B and C compared to the TDP on a standard disk. This difference in TDP is converted into a clearance gain value (i.e. a gain in clearance from that on a standard disk) using a conversion factor of $0.119 nm/mW$, which is the TFC efficiency estimated for ABS-2 from simulations. Fig 9 shows the same information in graphical form and highlights the linear relationship between the disk roughness (R_p or R_q) and clearance gain. Since the thermal protrusion comes into contact with the peaks of the roughness, the relationship between the clearance gain and R_p (Fig 9b) is of importance, and it is seen that for every $1nm$ decrease in R_p, there is a $0.8nm$ actual gain in clearance at the HDI for the range of surface roughness values considered in these experiments.

Next, the dependence of friction on the disk roughness is investigated by conducting a 'friction test' on each of the three disk types. A new (unburnished) slider is flown on a fresh test track, the TDP is determined, and the TFC heater is then supplied the power profile with a $100ms$ dwell time (as shown in Fig 8). The peak TFC power is increased from TDP to a maximum of $TDP + 50mW$ in $5mW$ increments, and it is then similarly decreased back to TDP. The average friction measured by the strain gage at each power step is tabulated. All tests are conducted on the same disk track. The measured friction values are plotted as those for the 'unburnished' case. The same slider, which is now deemed 'burnished' because of the overpush testing, is flown on an adjacent track and the friction test is repeated to obtain friction values for the 'burnished' case. Fig 10a shows a representative plot for the strain gage measured friction values as a function of overpush power supplied to the TFC heater.

A quadratic curve passing through the origin is fit to the friction measurements for the 'unburnished' and 'burnished' cases, and the slope of this curve at the $10mW$ overpush point is used to obtain the 'friction (μN) per *milliwatt* of overpush power' value. Fig 10b plots these friction values measured on the three disk types (A,B and C) based on experiments conducted with three new sliders on each disk type. While there is no particular trend relating the measured friction and surface roughness, the friction is higher for the burnished slider compared to the unburnished slider in all tests. Slider burnishing increases the actual contact area between the thermal protrusion and the disk, thereby resulting in the slightly higher friction force.

In order to directly compare the friction values between the three disk types, another set of experiments is conducted by flying the same 'burnished' slider (burnished in a controlled fashion separately) on the three disk types in succession. The friction against the overpush power is plotted in Fig 10c using data from two 'burnished' heads. It is concluded that there is no significant effect of the disk surface roughness on friction based on these results.

3. *Effect of lubricant parameters*

Friction tests are conducted to determine the effect of lubricant type/bonding on the friction in contact. Disks with three different lubricant type/bonding ratios are used: Lube A (61% bonded ratio, 10.5Å), Lube A (69% bonded, 10.5Å) and Lube B (82% bonded, 12Å). Fig 11a shows the friction measured for the three media for the unburnished and burnished cases (based on three experiments each). The friction values are comparable for the unburnished case for all three disks types. While the friction values for the burnished and unburnished cases are comparable for the disks with Lube A 61% and 69% bonded ratio, the friction for the burnished case on the disk with Lube B 82% bonded ratio is relatively higher than the unburnished case. This result is conistent with results for the change in TDP occurring because of a friction test, since the TDP change after and before a friction test is a measure of slider burnishing. As shown in Fig 11b, the highest burnishing (indicated by highest δTDP) occurs with an unburnished slider on the Lube B 82% bonded disk, and as a result, the friction is higher for the subsequent test conducted with this burnished slider.

A direct comparison of friction values is reported in Fig 11c based on tests conducted in succession on the three different disks using two 'burnished' sliders, and it shows marginally higher friction values for the disk with Lube B 82% bonded ratio.

Friction tests are conducted to understand the effect of the mobile part of the lubricant on friction and slider burnishing. The disk with Lube A 10.5Å 61% bonded fraction is delubed by immersing it in a solution of Vertrel XF solution to remove the mobile lubricant. The delubed disk has a lubricant thickness of 6Å (bonded lubricant). Fig 12a shows the measured friction on the lubed and delubed disks for the unburnished and burnished slider cases. While the friction values are comparable for the unburnished as well as burnished cases of the lubed disk and the unburnished case of the delubed disk, it is substantially higher for the burnished case of the delubed disk. Fig 12b shows that slider burnishing (indicated by δTDP after a friction test) is higher for tests conducted on the delubed disk implying that an unburnished slider is substantially burnished on this disk type, and the friction is higher for the subsequent test conducted with such a burnished slider. Therefore the mobile part of the lubricant plays an important role in reducing friction as well as slider burnishing, thereby increasing the reliability of a HDI with contact.

4. Effect of TFC efficiency

The thermal protrusion size and shape make a significant difference in the slider's touch-down and contact behavior. The friction during contact for different slider ABS/heater designs are plotted in Fig 13 for the unburnished and burnished cases, and the same data is tabulated in Table III together with each design's TFC efficiency estimated from simulations. It is observed that the friction forces increases as the TFC efficiency increases.

5. Effect of disk RPM

The similarities between the touchdown plot and contact signature of ABS-2 at different disk RPMs to those of ABS designs with different TFC efficiencies is highlighted in section III B. Particularly, it is shown that at a higher RPM, ABS-2 behaves like a design with low TFC efficiency (showing a gradual touchdown plot), and at a lower RPM, ABS-2 behaves like a design with high TFC efficiency (showing a sharp touchdown plot).

The friction results in tests with ABS-2 at different RPM are consistent with the above analogy and the results presented in section III D 4. Fig 14 shows that the friction increases as the disk RPM decreases, i.e. when ABS-2 is made to behave like a slider with high TFC efficiency by decreasing RPM it exhibits the characteristic sharp touchdown plot and higher friction.

IV. CONCLUSION

The touchdown behavior of TFC sliders is investigated through experiments. Certain sliders exhibit a sharp rise of acoustic emission (AE) signal at touchdown when the power is increased in milliwatt steps while others show a gradual rise making it difficult to exactly define the TDP to milliwatt resolution. An analogous behavior occurs when the disk RPM is changed for a particular slider ABS. It is found that the dominant modes/frequencies of excitation at touchdown are significantly different in these cases leading to the very different touchdown signatures. Particularly, the sharp touchdown case is characterized by strong individual contact events as observed in the AE signal, and the dominant excitation occurs at frequencies that correspond to the slider's first pitch and roll modes in addition to suspension related frequencies. In contrast, the gradual touchdown case is characterized by a uniform rise in AE signal over the duration of the TFC pulse, and the dominant excitation occurs at the slider's second pitch mode. The pressure under the TFC protrusion at touchdown, the TFC efficiency as well as the propensity for lubricant pick-up show correlation with touchdown behavior and may be used as metrics for designing sliders with good touchdown features. Experiments are devised to measure the friction at the HDI during TFC induced contact, and several parametric investigations are carried out. Disk surface roughness does not significantly affect the friction during contact. The mobile part of the lubricant plays an important role in reducing friction as well as slider burnishing. A burnished slider shows a higher friction value than an unburnished slider, and sliders with higher TFC efficiency show higher friction compared to sliders with lower TFC efficiency.

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ABS design	Simulation TFC efficiency nm/mW	Touchdown power mW	Pressure at touchdown $atm.$
ABS-1	0.108	96	60
ABS-2	0.119	91	38
ABS-3	0.145	69	27

TABLE I. Simulated results for the three different ABS designs

Disk	R_p nm	R_q nm	R_v nm	δTDP mW	Clearance gain nm
A	2.02	0.49	1.87	0.08	0.01
B	1.89	0.36	1.47	0.97	0.12
C	1.00	0.24	1.11	6.71	0.84

TABLE II. Disk roughness parameters and its effect on TDP/clearance gain

ABS design	Simulation TFC efficiency nm/mW	Friction Unburnished $\mu N/mW$	Friction Burnished $\mu N/mW$
ABS-A	0.108	9	17
ABS-B	0.111	24	31
ABS-C (ABS-2)	0.119	37	54
ABS-D (ABS-3)	0.145	56	67

TABLE III. Effect of TFC efficiency (ABS/heater design) on friction

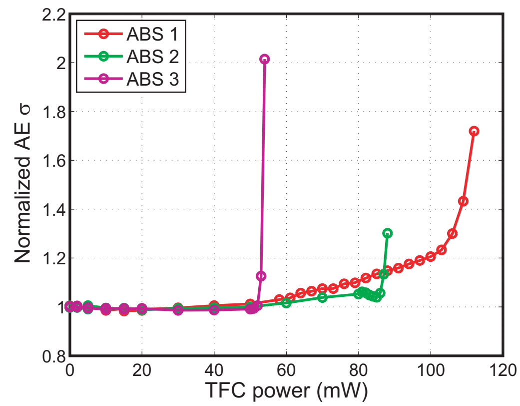

FIG. 1. Touchdown plots for the three different ABS designs

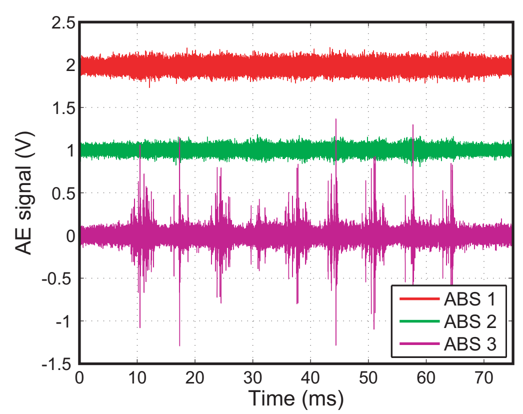

FIG. 2. Touchdown signature for the three different ABS designs (plots offset by $1V$ for clarity)

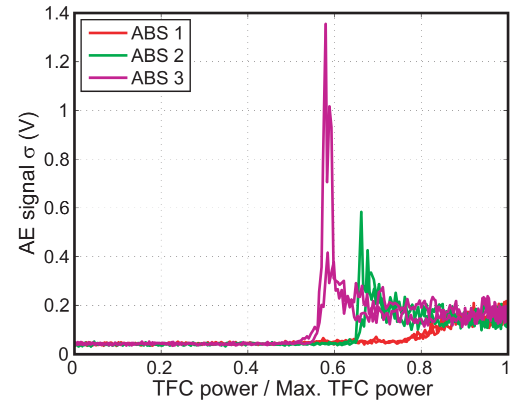

FIG. 3. Contact behavior in overpush for the three different ABS designs

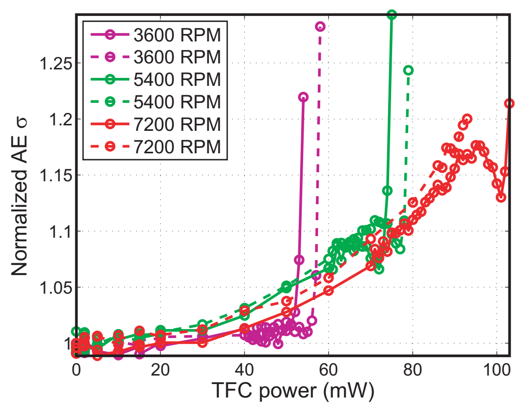

FIG. 4. Touchdown plots for ABS-2 at different disk RPM (dashed lines for a burnished slider)

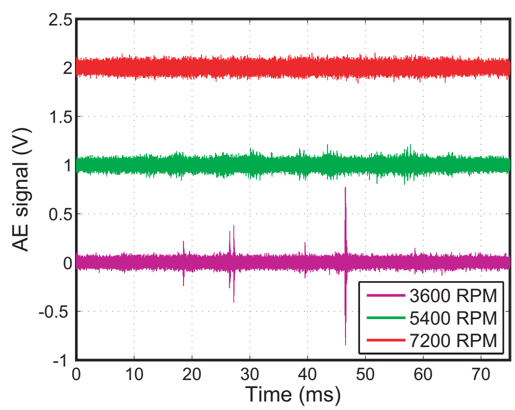

FIG. 5. Touchdown signature for ABS-2 at different disk RPM (plots offset by $1V$ for clarity)

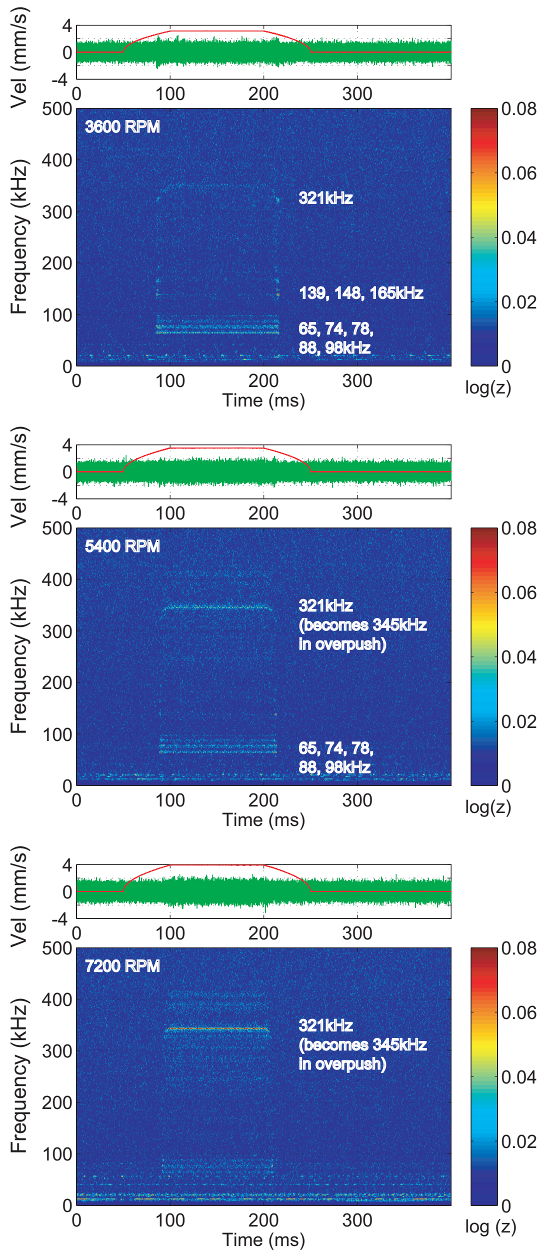

FIG. 6. Vertical velocity time history and the JFT of vertical velocity for ABS-2 at different disk RPM

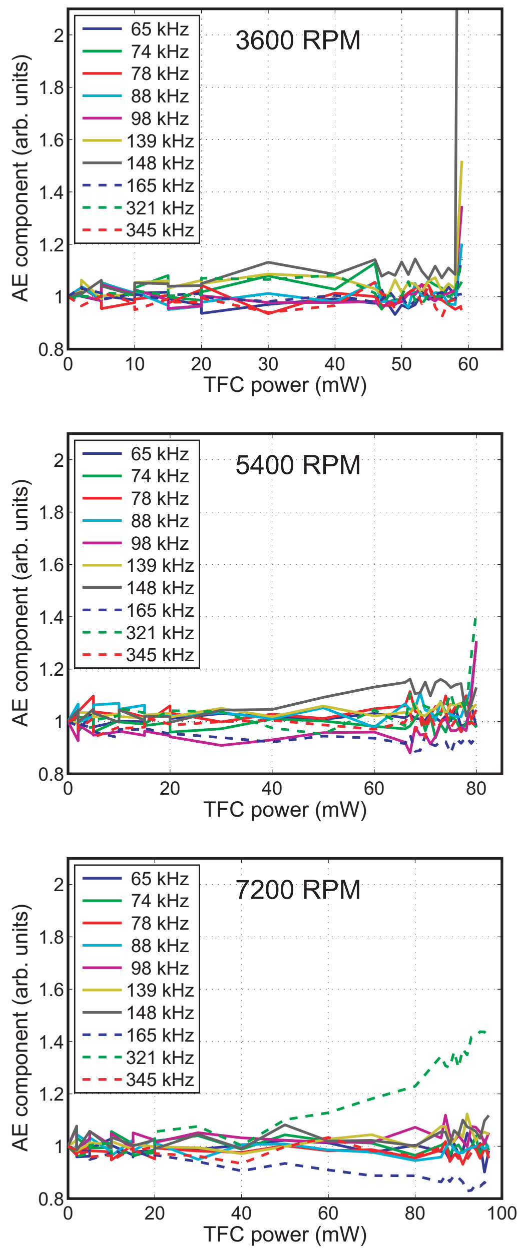

FIG. 7. AE signal components in the touchdown plot for ABS-2 at different disk RPM

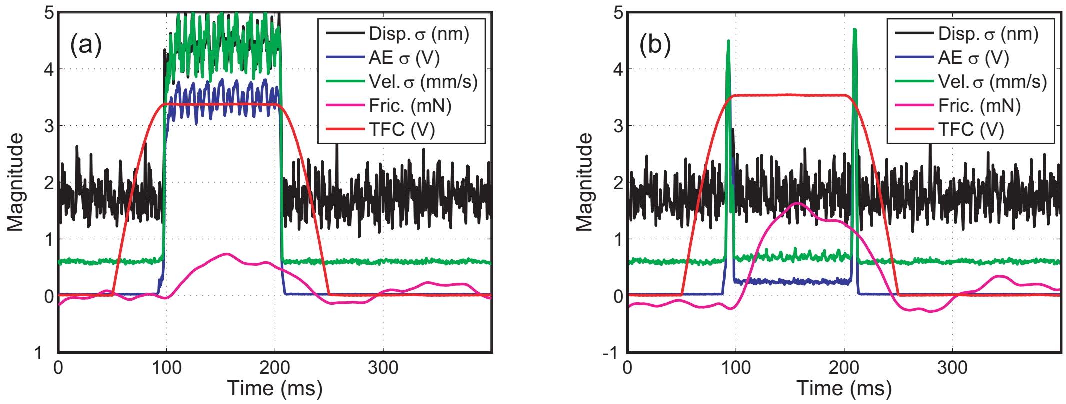

FIG. 8. Time history of TFC power, vertical displacement, vertical velocity, AE signal and friction (a) $10mW$ overpush (b) $20mW$ overpush

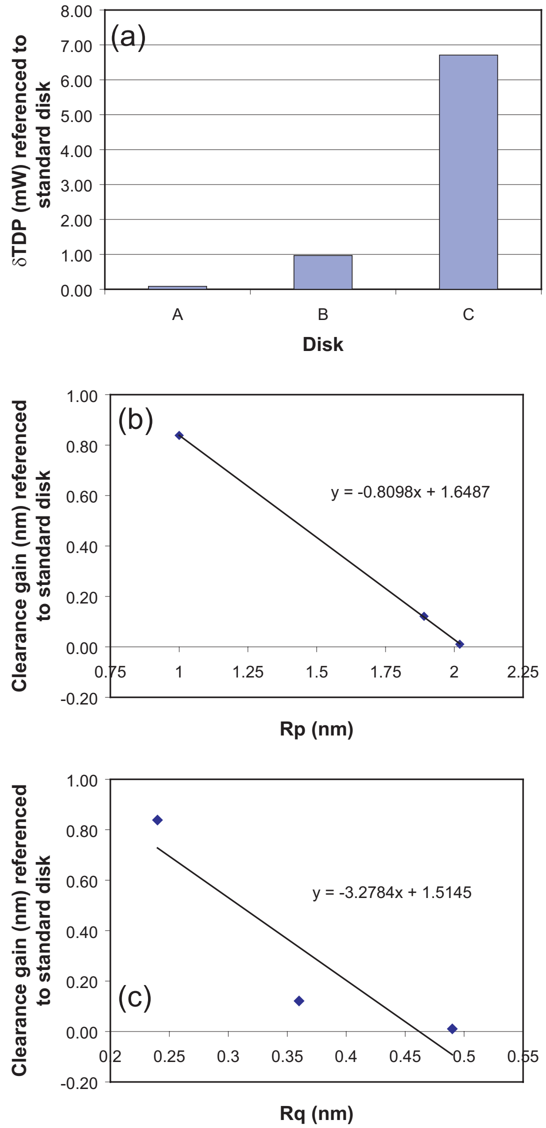

FIG. 9. Effect of disk roughness on clearance

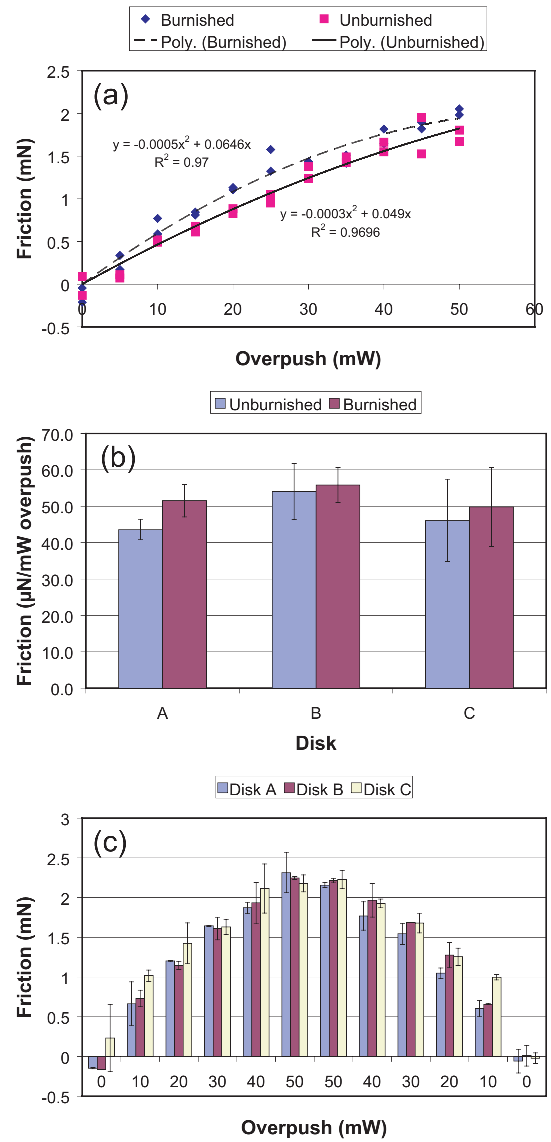

FIG. 10. Effect of disk roughness on friction

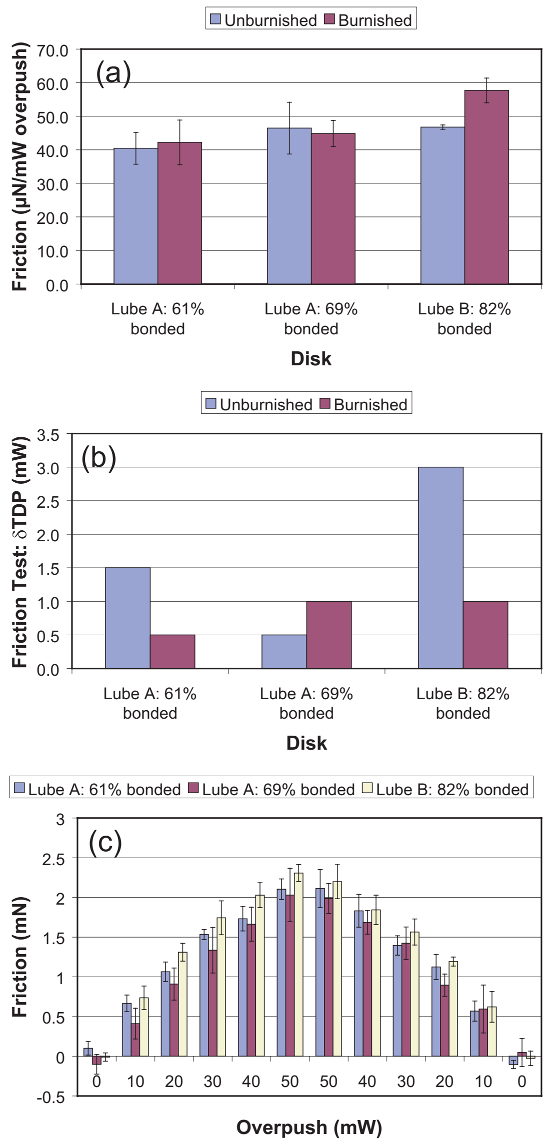

FIG. 11. Effect of lubricant parameters on friction and slider burnishing

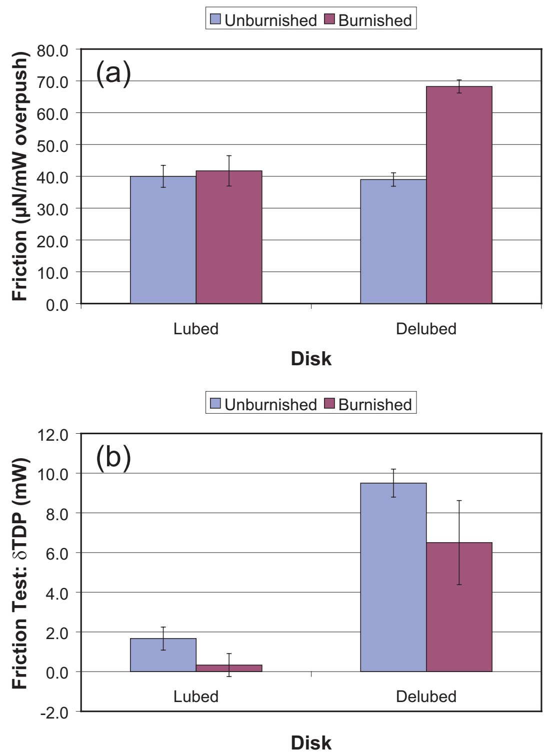

FIG. 12. Effect of mobile lubricant on friction and slider burnishing

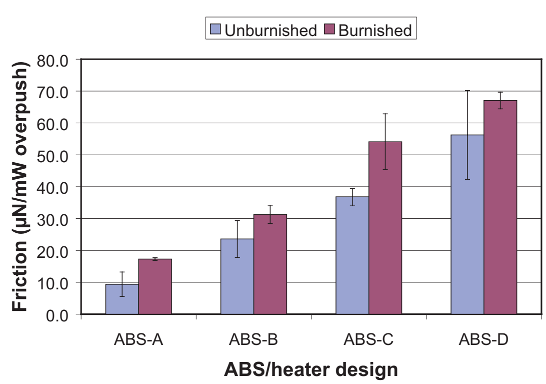

FIG. 13. Effect of TFC efficiency (ABS/heater design) on friction

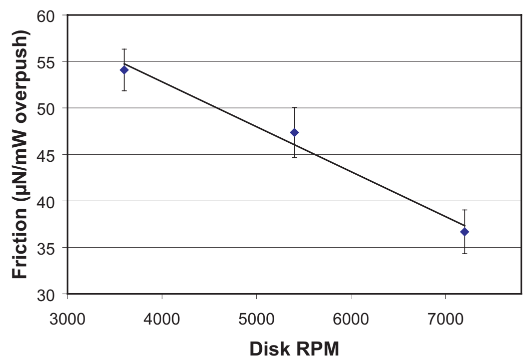

FIG. 14. Effect of disk RPM on friction for ABS-2