Critical Clearance for Slider-Lubricant Interactions at the Head-Disk Interface in Hard Disk Drives

Rohit P. Ambekar and David B. Bogy
Computer Mechanics Laboratory,
Mechanical Engineering,
University of California, Berkeley, CA, USA
Email: rohit@cml.me.berkeley.edu

C. Singh Bhatia
Hitachi Global Storage Technologies, San Jose, CA, USA

Abstract

This letter reports the results of experiments that suggest the existence of a critical clearance between the flying head (slider) and the disk, above which there is negligible slider-lubricant interaction and at which the slider-lubricant interaction starts and increases in intensity as the clearance between head and disk further reduces. Using shear stress simulations and previously published work we develop a theory to support the experimental observations. Decreasing the slider-lubricant interaction is necessary for reliability of the head-disk interface, while reduction in head-disk clearance is a requirement for increasing the areal density. It appears that the critical clearance can be reduced through proper design of the interface.

Introduction:

In order to attain a very high areal density of 2Tb/in.^{2} in hard disk drives, the head-disk clearance has to be reduced to below 2 nm. A variety of proximity interactions such as intermolecular, meniscus and electrostatic forces, influence of disk topography, etc., tend to destabilize the airbearing slider at this spacing, making this goal a substantial challenge. Several studies of these proximity interactions have been reported, however there has been no consensus on what phenomenon primarily affects slider stability the most. Some researchers indicate that intermolecular forces (IMF) provide attraction between the slider and the disk at sub-5nm spacing, and it is an important factor affecting the head stability [1-3]. Electrostatic forces (ESF) developed at the head-disk interface due to tribocharging [4-6] also cause attraction between head and the disk. Recently the study of slider-lubricant interaction has gained much attention as it significantly affects the head stability [7-9]. Lubricant, the topmost layer on the disk, is transferred to negative pressure sliders (which are currently used) even in the absence of any head-disk contact. This causes contamination of the airbearing surface (ABS) of the slider and also removes the protective lubricant layer from the disk, which severely affects the reliability of the hard drive. Thus, reduction in slider-lubricant interactions is important for ensuring reliability in current products as well as for attaining higher areal density in future drives.

Experimental:

To study slider-lubricant interactions we used half-delubed disks following Ma et. al. [10] as shown in Figure 1. When the slider is flown over such a disk on any track, it spends equal time on the lubed and delubed parts of the disk during each revolution. This helps in studying slider-lubricant interactions as the slider picks up lubricant from the lubed part and deposits it on the delubed part. The process dynamics are discussed in some detail elsewhere [11]. The lubricant used in the experiments was Zdol, with varying thickness, bonded ratio and molecular weight. The carbon overcoat was 2.7 nm thick and of the type CHxNy with x:y = 1:1.4. The base substrate for the disks was AlMg, 50 mils (1.27mm) thick and 95 mm in diameter. Various ABS designs were used for the experiments (one design is shown in Figure 2), which were conducted in-situ on a Candela Optical Surface Analyzer (OSA) equipped with an ellipsometer to measure the change in the disk lubricant with a sub-Å accuracy. A sensitive acoustic emission (AE) sensor was mounted near the suspension base plate to monitor head-disk contact. In addition, a Polytec Laser Doppler Vibrometer (LDV) was focused on the slider to monitor its dynamics, which also provided an additional method of detecting contact. Very good correlation was observed in the AE and LDV contact detection.

The experimental procedure was as follows. The disk was mounted on the OSA spinstand and spun at a high rpm (17K), and then the slider was loaded onto a track and moved to a different fresh track. The disk rpm was maintained for a certain period and then reduced by increments of 1000 rpm to 11000 rpm, after which it was reduced by 500 rpm increments to 9000 rpm followed by 100-200 rpm reductions until substantial slider-lubricant interaction was observed. The rpm was then further reduced until the AE and LDV detected head-disk contacts to determine the touchdown rpm/velocity.

There was no change in the lubricant at high rpms even when the tests were monitored for a long time, as shown in Figure 2(a-d). Only when the rpm was reduced to a particular value was there some change, such as depletion and modulation (Figure 2(e)). We refer to this rpm/velocity as the critical velocity and the associated head-disk clearance as the critical clearance. Upon conducting multiple runs, we found a good repeatability (3σ of error ~ 600rpm=0.30nm) in the value of critical clearance, determined from the difference between the critical velocity and the touchdown velocity. The values of critical clearances observed were in the range of 0.5 -3.5 nm depending on the slider and disk designs, as shown in Figure 3, which shows critical clearances for Zdol lubricant with different molecular weights, different carbon substrates (CHx and CHxNy) and with inclusion of additives X1-P and A20H. It is seen that the critical clearance increases with increasing lubricant molecular weight, the inclusion of additives and for CHx.

Simulations:

To understand the physics of the process and explain the observed trends, we conducted airbearing simulations for models of the experimental sliders using CMLAir, a finite-volume based software developed at CML to solve the Reynolds equation. Steady-state fly heights of sliders and pressures were obtained at various rpms and radial positions that matched the experiments. Using this data, we obtained the shear stress (γ_x) for the first-order slip model (Equation 1), which has been shown to give results close to those obtained by Kang's model using kinetic theory [12,13].

In Equation 1, μ_{air} is the viscosity of air, U is the disk velocity, a is the accommodation coefficient while h and P are the slider-disk clearance and airbearing pressure at a particular point on the slider, respectively, and λ is the mean-free path of the air molecules. Equation 2 shows the dependence of λ on pressure, where λ_0=63.5 nm is the mean free path of air molecule at STP. Using this formulation, we calculated the shear rate($\dot{\gamma}_x$) and total shear force (F_x^{shear}) as shown in Equations 3 and 4, respectively.

$$\gamma_x = \mu_{air} \frac{U}{(2a\lambda + h)} - \frac{\partial P}{\partial x} \frac{h}{2} \tag{1}$$

where, $$\lambda = \lambda_0 / P \tag{2}$$

Further, $$\dot{\gamma}_x = \frac{d\gamma_x}{dt} = \frac{d\gamma_x}{dx}\frac{dx}{dt} = \frac{d\gamma_x}{dx} \times U \tag{3}$$

and $$F_x^{shear} = \sum \gamma_x (dx \cdot dy) \tag{4}$$

The total shear force and maximum shear rate are plotted in Figure 4 for the ABS design shown in Figure 2. It is seen that both of these quantities decrease with decreasing rpm/velocity even if the decreasing disk velocity leads to lower slider fly height and pitch. This presents somewhat of a paradox as shear force has been shown to be the most important factor affecting the lubricant by various researchers [14,15] and we see increased head-disk interaction at lower disk velocity. Further, the total vertical positive and negative force also decrease with decreasing disk rpm/velocity. Thus, the decrease in pressure as well as shear with decreasing rpm is unable to explain the increased slider-lubricant interaction observed at lower clearances unless the lubricant is of shear-thickening type, i.e. behaving more like a fluid at lower shear and shear-rates. However, some experiments in the literature show PFPE lubricants to be of Newtonian type [16] or a shear-thinning type (as most polymers) in the thickness range of 5-10 nm [17]. But it still remains to be proven for the thickness range used in the current experiments.

Discussion:

Various external non-contact forces like airbearing pressure, shear, IMF and ESF act on the lubricant. Only IMF and ESF increase with decreasing head-disk clearance under decreasing disk velocity and can explain the experimental observations. Since disk was well grounded in the experiments conducted, we assume effect of ESF as negligible. Even in presence of ESF, the following analysis will hold since there is monotonic increase in the force with decreasing head-disk clearance.

Dagatine et. al. [18] investigated the effect of van der Waals forces (IMF) on disk lubricant using Lifshitz theory to calculate the disjoining pressure of the disk lubricant in the presence of the slider. They found that the lubricant disjoining pressure decreases with decreasing head-disk spacing and becomes negative at a particular spacing. Because negative disjoining pressure implies instability/dewetting, their calculations also suggest the existence of a critical clearance, below which the lubricant is affected by the slider due to the increase in the IMF although the interaction only sets up lubricant modulations and does not explain the lubricant transfer to the slider. Further, in their calculations, the lubricant layer was considered to be a continuum, and other forces such as airbearing shear and pressure were not considered, which may accelerate or delay the destabilization process. Nevertheless, the magnitude of the IMF at low clearance is relatively high and so the prediction of these calculations may still be valid. We build on their theory here and present two related physical mechanisms to explain the observed phenomenon. It is first noted that the thin lubricant layer (close to a monolayer) is only approximated by continuum. Thus, a look at the molecular level is essential to understand and explain the possible mechanisms.

Figure 5 shows a schematic of lubricant polymer molecules adhered to the carbon layer. A rich literature exists on the interaction between the active sites in carbon and the lubricant. It has been shown that active polymer endgroups bind to the active carbon sites responsible for lube-carbon adhesion, while their backbones remain coiled and extend upwards contributing to "molecular roughness." [19] The lower lubricant layer bonds well with the carbon layer to form the 'bonded' layer while the upper layer is a 'mobile' layer having more mobility. Cohesion between lubricant molecules plays a much more important role in the mobile layer than the adhesion between lube-carbon in the bonded layer. Based on this concept, we propose that the combined action of shear, pressure and IMF leads to increased slider-lubricant interaction even if the shear reduces with the reduction in fly height under reduced rpm.

To calculate the IMF more precisely, a multilayer model could be employed [3] using a ‘lube centered approach’ [18]. However, the qualitative trend in IMF (increase with decreasing clearance) is enough to explain the mechanisms. At low clearances, the topmost layer of lube is pulled to the slider by the IMF along with suction pressure in case of negative pressure sliders, and it is kept on the disk by cohesion between the lube molecules and IMF from the disk, as shown in Figure 5. At the (critical) clearance where the IMF from the slider becomes greater than the forces holding the lubricant molecule on the disk viz. cohesion and IMF from the disk, the lubricant molecule is loosened or pulled away from the disk surface to be atomized. This is one physical mechanism explaining the observed phenomenon. The second mechanism is the secondary effect of the increased IMF. There might be preferential pulling of the lubricant backbone, which stretches the molecule in the vertical direction. This increases its normal surface area to the airbearing shear. Hence, even if the magnitude of the shear stress decreases, the total shear force experienced by the stretched lubricant molecule could increase. Also, increased molecular roughness increases the surface area of the molecule to the airbearing shear. Thus, we can estimate by using this theory that destabilization of the lubricant layer [18], which increases the molecular roughness, aids increased slider-lubricant interaction and increases the critical clearance. When experiments were conducted on tracks where the lubricant was already modulated, this was indeed seen to be the case.

By the mechanisms described above, higher molecular roughness and lower cohesion/adhesion increase the critical clearance as they decrease the forces holding the lubricant molecules to the disk. Since higher molecular weights have higher molecular roughness [19] and lower bond density, they should have higher critical clearance. Additives X1-P and A20H have a relatively large phosphazene ring [20] which increases their molecular roughness. Further, X1-P is also reported to preferably occupy bonding sites thus decreasing the adhesion of Zdol [21]. On the other hand, in A20H the phosphazine ring, which is one endgroup of the chain, does not adhere to the carbon. This leaves only the other active OH endgroup to adhere, which decreases the overall adhesion of the lubricant [20]. This explains the increased critical clearance with inclusion of these additives. Finally, research on CHx and CNx overcoats [22] suggests that the inclusion of nitrogen leads to better lubricant coverage, stronger adhesion with carbon and possibly more lubricant entanglement due to repulsion of the basic lubricant backbone by nitrogen moieties, which exposes more active sites on carbon. This explains the decrease in critical clearance on CHxNy as compared to CHx.

Thus, the mechanisms indicated above can explain the increase in slider-lubricant interactions in spite of lower shear at lower clearance and lower disk velocity. They also explain the criticality associated with the slider-lubricant interactions and the trends shown in Figure 3.

Acknowledgements:

The authors would like to thank T. Watanabe and A. Furuta of Fuji Electric Co. for providing disks used in this study and Dr. R. Waltman and Dr. B. Marchon of Hitachi GST for helpful discussions. This work was supported by the Computer Mechanics Laboratory at the University of California, Berkeley, USA and the Information Storage Industry Consortium's EHDR Program.

References:

[1] L. Wu and D.B. Bogy, ASME J. Tribol **124** 567 (2002)

[2] J.H. Li, B. Liu, W. Hua and Y.S. Ma, IEEE Trans. Magn **38** 2141 (2002).

[3] R.P. Ambekar, V. Gupta and D.B. Bogy, ASME J. Tribol. **127** 530 (2005)

[4] J.D. Keily and Y-.T. Hsia, J. Appl. Phys. **91** 4631 (2002)

[5] M. Suk, R. Kroeker and D. Gillis, Microsys. Tech. **9** 256 (2003)

[6] V. Gupta and D.B. Bogy, IEEE Trans. Magn. **41** 610 (2005)

[7] R.P. Ambekar and D.B. Bogy, IEEE Trans. Magn. **41** 3028 (2005)

[8] H. Matsuoka, S. Fukui and T. Kato, IEEE Trans. Magn. **39** 864 (2003)

[9] S.K. Chilamakuri and B. Bhushan, J. Appl. Phys. **86** 4649 (1999)

[10] X. Ma, H. Tang, M. Stirniman and J. Gui, IEEE Trans. Magn **38** 2144 (2002)

[11] R.P. Ambekar, D.B. Bogy and C.S. Bhatia, ASME J. Tribol. (in press)

[12] S-.C. Kang, PhD Dissertation, Carnegie-Mellon Univ. (1997).

[13] D. Chen and D.B. Bogy, CML Tech Report 2005-10.

[14] Q. Dai, F. Hendriks and B. Marchon, J. Appl. Phys. **96** 696 (2004)

[15] H. Kubotera and D.B. Bogy,

[16] C.M. Mate and B. Marchon, Phys. Rev. Lett. **85** 3902 (2000)

[17] M. Ruths and S. Granick, Trib. Lett. **7** 161 (1999)

[18] R.R. Dagastine, L.R. White, P.M. Jones and Y-.T. Hsia, J. Appl. Phys. **98** 124906 (2005)

[19] A. Khurshudov and R. J. Waltman, Trib. Lett. **11** 143 (2001)

[20] R.J. Waltman, N. Kobayashi, N. Shirai, A. Khurshudov and H. Deng, Trib. Lett. **16** 153 (2004)

[21] C-.Y. Chen, D.B. Bogy, T. Cheng and C.S. Bhatia, IEEE Trans. Magn. **36** 2708 (2000)

[22] G. W. Tyndall, R.J. Waltman and D.J. Pocker, Langmuir **14** 7527 (1998)

Figures:

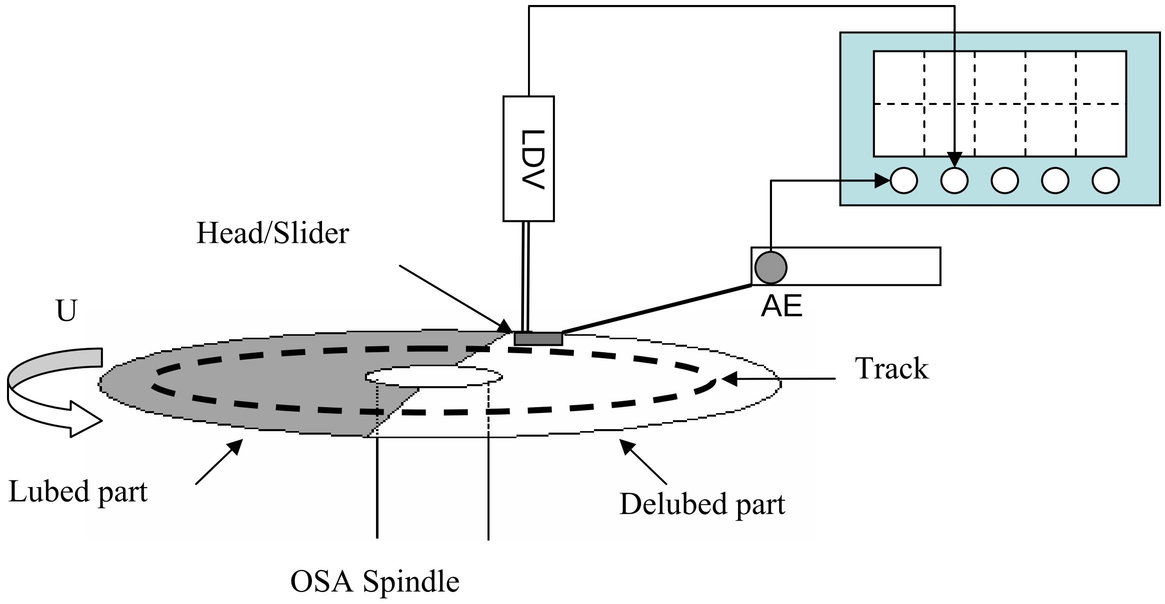

FIG. 1: Experimental setup for studying slider-lubricant interaction

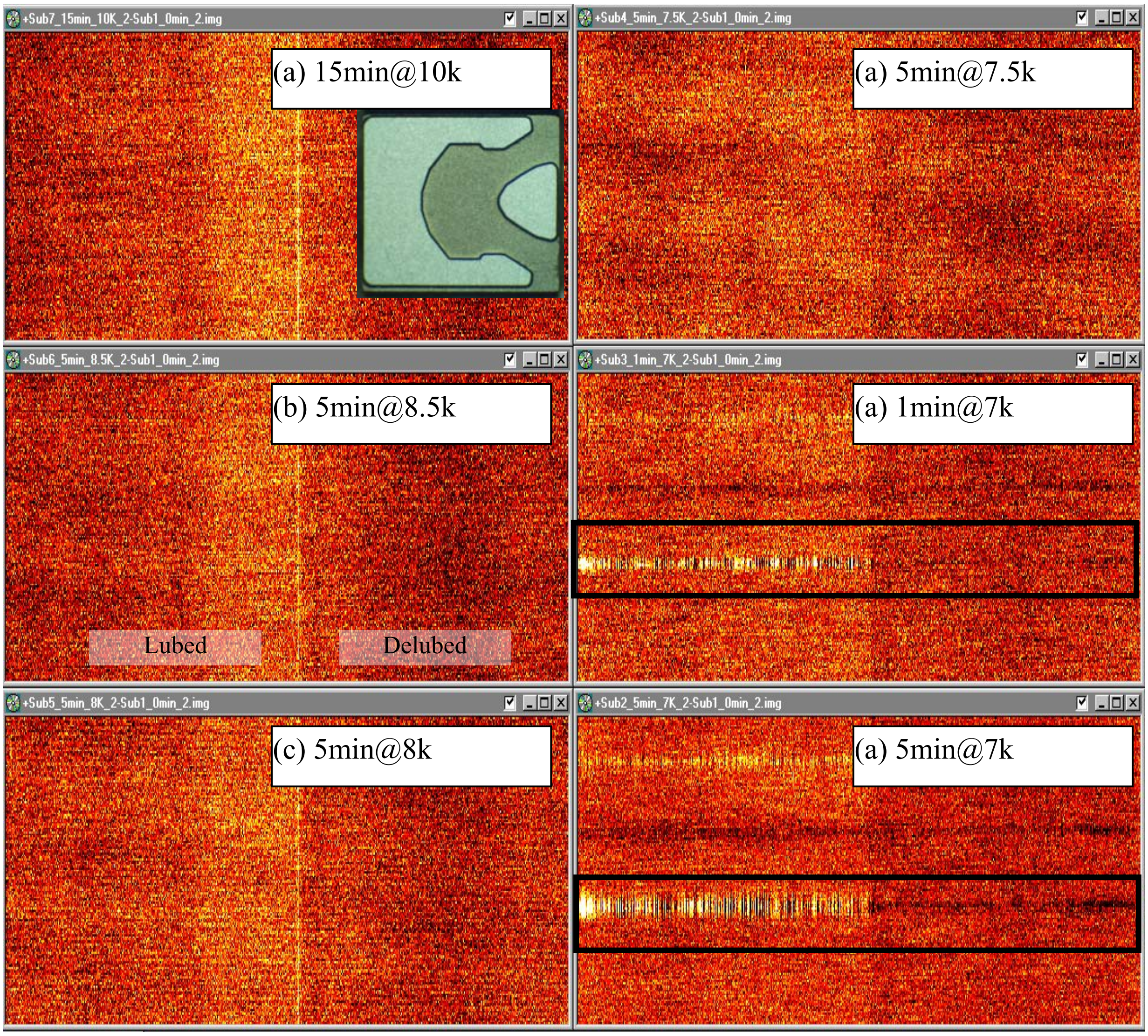

FIG. 2: OSA images showing lube change at various rpms

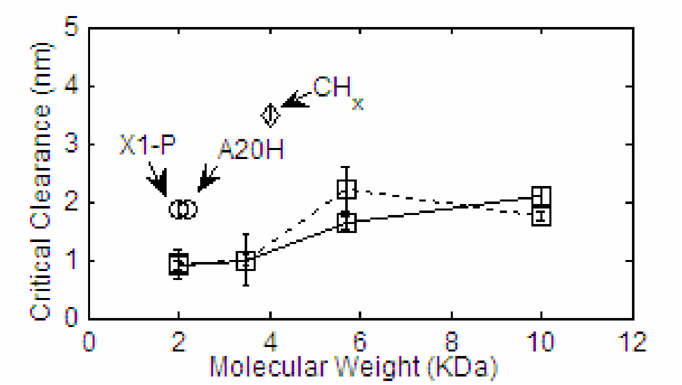

FIG. 3: Critical clearance as a function of lubricant molecular weight, additives and carbon overcoat type.

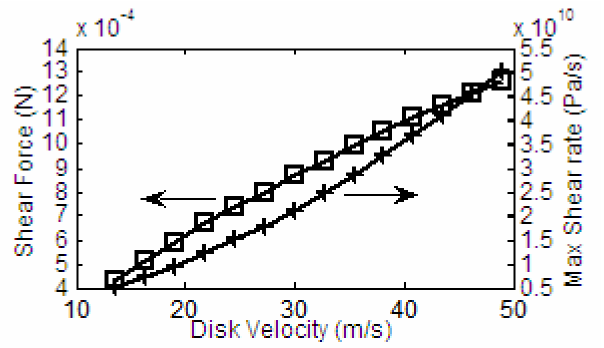

FIG. 4: Variation of shear force and maximum shear rate with disk velocity

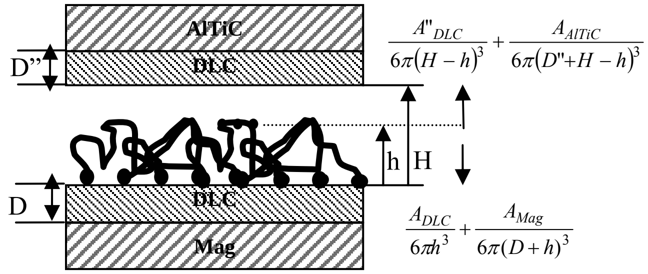

FIG. 5: Molecular view of disk lubricant