Tribology and Nano-Tribology Problems in Data Storage on Hard Disks

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Abstract

In current "state of the art" disk drives, the flying height between slider and disk is on the order of 10 nm. The flying height will need to be reduced to approximately 3 nm to meet future storage density goals. At a spacing of 3 nm, severe tribological problems will occur with respect to friction, wear and lubrication of the head/disk interface. In this paper, tribology and nano-tribology problems of the head/disk interface are examined as the recording density is increased towards 1Tbit/inch^2.

1. INTRODUCTION

Magnetic recording has become the main technology for the storage of digital data. With the introduction of hard disk drives in consumer products such as video recorders or cell phones, the demand for high performance hard disk drives continues to increase at a rapid pace. Storage densities on the order of 120Gbit/in^2 have been achieved allowing the storage of 200Gbytes of data on a double sided 96 mm form factor hard disk. Storage of information in hard disk drives is accomplished by the relative motion between a rotating magnetic disk and a magnetic read/write element supported by an air bearing slider. The separation between the slider and the hard disk, known as flying height, is one of the most important parameters that controls the performance of a hard drive. In order to increase the recording density, it is necessary to decrease the flying height between slider and disk. Ideally, zero spacing between the read/write transducer and the magnetic disk is desired.

In present-day hard disk drives the flying height is on the order of 10 nanometers (nm). To increase the storage density from the current 120 Gbit/inch^2 to 1 Tbit/inch^2, the spacing between slider and disk must decrease to approximately 3nm (Wood, 2000). In order to design a reliable head/disk interface for these conditions, care must be exercised in designing the air bearing, in minimizing surface roughness effects between the slider and the disk, and in optimizing all tribological issues occurring at the head/disk interface.

This paper presents an overview of important tribological problems encountered in magnetic recording disk technology and highlights those problems that need to be solved as the recording density is increased to 1 Tbit/inch^2. In addition, the paper addresses nano-tribology problems that will become critical issues in future disk drives when alternative technologies, such as heat assisted magnetic recording or bit patterned media technology, must be implemented.

2. OVERVIEW OF THE HEAD/DISK INTERFACE

A typical disk drive consists of one or more hard disks mounted on a hub driven by the spindle motor. A slider is attached to a suspension spring which positions the read/write transducer in close proximity to the disk surface. During rotation of the disk, an air bearing is formed between slider and disk (Figure 1). A nickel phosphorous under-layer is deposited on aluminum disks before the magnetic layer is applied. The magnetic layer on the disk surface is protected by a thin carbon film on the order of 3 nm thickness. A lubricant film approximately 1 nm thick is applied by dip coating to protect the carbon film. Figure 2 shows a schematic view of the layer structure of a typical disk.

One of the key parameters affecting the resolution of the read back signal in a hard disk drive is the flying height, i.e., the spacing between slider and disk. A graph showing the decrease in flying height in commercially available disk drives over the last fifty years is shown in Figure 3. Over the same time period, the storage density has increased by a factor of 35 million.

Figure 1 head/disk interface

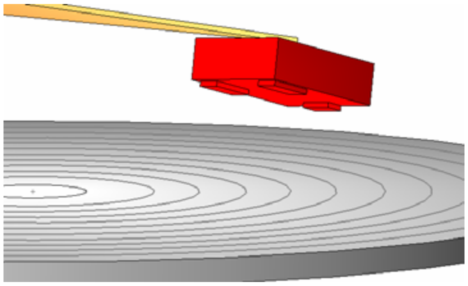


Figure 2 Layered structure of disk

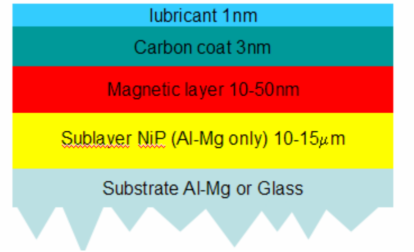
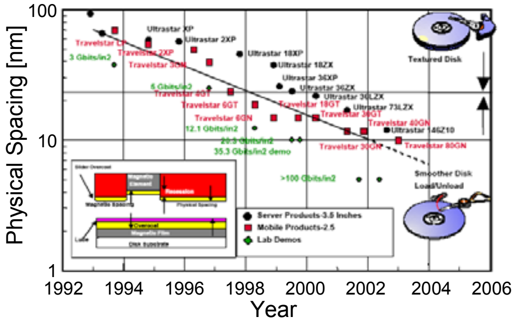


Figure 3 Flying height decrease of magnetic recording disk drives as a function of year of first shipment (source: Hitachi GST)



3. EQUATIONS DETERMINING THE FLYING OF A MAGNETIC RECORDING SLIDER

The equations determining the flying of a magnetic recording slider are the modified Reynolds equation with Boltzmann correction terms (Fukui & Kaneko, 1988), given by

$$\frac{\partial}{\partial x}\left(\bar{Q}ph^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\bar{Q}ph^3\frac{\partial p}{\partial y}\right)=6\mu\left(U\frac{\partial ph}{\partial x}+V\frac{\partial ph}{\partial y}\right)+12\mu\frac{\partial ph}{\partial t} \tag{1}$$

and the slider equilibrium equations, given by

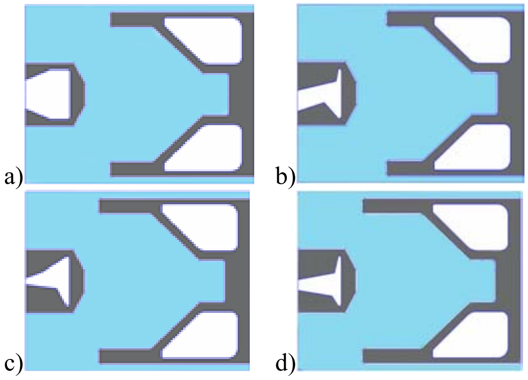
$$\begin{Bmatrix} \iint_A p(x,y)dA - F_z^{ext} \\ \iint_A p(x,y)(x-x_p)dA - M_\alpha^{ext} \\ \iint_A p(x,y)(y-y_p)dA - M_\beta^{ext} \end{Bmatrix} = \begin{bmatrix} k_z & 0 & 0 \\ 0 & k_\alpha & 0 \\ 0 & 0 & k_\beta \end{bmatrix} \begin{Bmatrix} dh \\ d\alpha \\ d\beta \end{Bmatrix} + \begin{Bmatrix} F_z^{vdW} \\ M_\alpha^{vdW} \\ M_\beta^{vdW} \end{Bmatrix} \tag{2}$$

In equation (1), *p(x,y)* describes the pressure field of the air bearing slider, μ is the dynamic viscosity of air, U and V are the velocity components in the x and y directions, respectively, and Q represents the Boltzmann correction for rarefied gas flow. In equation (2), F_z^{ext} , M_α^{ext} and M_β^{ext} represent suspension load and moments in the vertical (*z*), pitch (α) and roll (β) directions, respectively, while k_z, k_α and k_β represent the components of suspension stiffness. The terms F_z^{vdW} , M_α^{vdW} and M_β^{vdW} represent intermolecular forces due to van der Waals interactions and electrostatic effects.

4. OPTIMIZATION OF AIR BEARING DESIGN FOR VERY LOW FLYING

Optimization of air bearing sliders is an important goal in designing high performance disk drives, and a number of research papers are in the open literature dealing with this subject. One of the first slider optimization papers was published by O'Hara and Bogy (1995), who used the genetic algorithm method to study the dependence of the slider contour on flying height and slider attitude. Other methods such as the DIRECT method (Zhu & Bogy, 1995), the sub region approach (Hanke & Talke, 2002) or simulated annealing (Zhu & Bogy, 2000) have also been applied. In Zhang & Talke, (2003) a comparison of the genetic algorithms and the sub region approach for slider bearing optimization is given. Zhang & Talke (2005) combined the genetic algorithm and the subregion approach using a finite element approach. Starting from a 14 nm "high flying" pico slider design, the authors studied three test cases for target flying heights of 7nm, 5nm and 3.5nm, respectively. The optimized air bearing surfaces for the trailing edge region of pico sliders using this "hybrid" algorithm are shown in Figure 4.

Figure 4 a) Original Design (FH=14nm), Optimized design for b) FH=7nm, c) FH=5nm, d) FH=3.5nm



5. SHOCK MODELING OF THE HEAD-MEDIA INTERFACE

Shock modeling of the head/disk interface is of great interest (Kumar et al, 1994), (Allen & Bogy, 1996), (Jayson & Talke, 2001) for evaluating the performance of hard disk drives. With the introduction of small form factor disk drives in consumer products such as cell phones and digital cameras, the shock performance of hard disk drives is an increasingly important parameter.

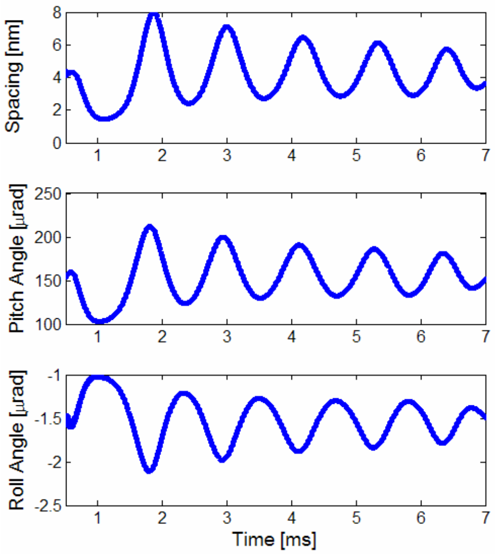
To predict and simulate the performance of a disk drive with respect to shock loads, a complete model of an operational hard disk drive (HDD) subject to impulsive type shock loads was developed (Jayson et al, 2001). The model is based on a coupled solution of the deflection of the structural components of a disk drive and the Reynolds equation governing the flow between slider and disk. The model uses a finite element simulation of the hard disk drive structural components using commercially available software packages and a specially developed finite element solution of the Reynolds equation to determine the pressure and spacing between the head and the disk.

In Figure 5, typical numerical results are shown for the *z*-displacement, as well as the pitch and roll motion of a slider subject to an external shock.

6. SLIDER VIBRATION REDUCTION USING SLIDER SURFACE TEXTURE

The tribological performance of the head/disk interface is strongly influenced by the surface roughness of the air bearing surface. Many investigations (Zhou et al, 2000, Xu et al, 2001, Zhou et al, 2002) have shown that texture of the air bearing surface improves the tribology of the head/disk interface.

Figure 5 Simulation of slider shock response

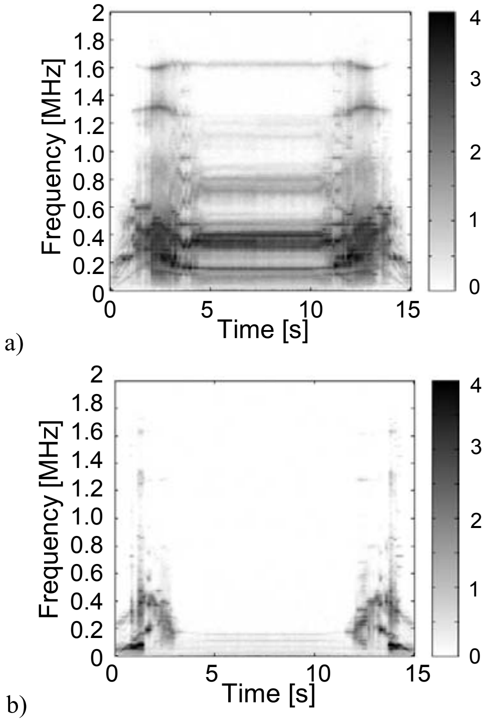


In Zhou et al (2003), ion etching was implemented to obtain an island type texture with a texture height of 4.5 nm on the slider surface of a pico-type slider. The in-plane and out-of-plane vibrations of textured and untextured sliders were investigated using laser Doppler vibrometry (LDV) during contact start/stop. Time frequency analysis of the out-of-plane slider vibrations for an un-textured and a textured slider is shown in Figure 6a) and 6b), respectively. The results indicate that the amplitudes of the out-of-plane vibrations are reduced as a consequence of the texture on the slider surfaces. A similar reduction of in-plane vibration is also observed.

7. ALTERNATIVE APPROACHES TO INCREASE THE STORAGE DENSITY

The studies discussed in the previous sections highlight some of the critical issues of the head disk interface in near contact recording situations, and show that the flying height between slider and disk is one of the most critical parameters. Since it is increasingly more difficult to reduce the flying height further, i.e., to values in the low sub-10 nm spacing range, the question arises whether one could possibly eliminate the flying of a slider altogether and implement "contact recording", where the spacing between the slider and the disk is zero.

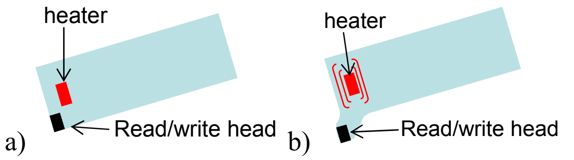
Figure 6 Out-of-plane vibrations for a) untextured and b) textured slider



Various investigations of contact recording have been undertaken in the past, starting as early as 1963 (Brock, 1963) and continuing to date (Hamilton et al, 1991, Talke, 1997, Itoh et al, 2001, Singh et al, 2004). Although contact recording is most desirable from the point of view of magnetics and signal resolution of the read signal, issues related to materials, tribology, and especially wear (Machcha & Talke, 1996, Kawakubo, 1995 & 2003) have prevented this approach from becoming reality. Based on Archard's law, it is apparent that wear of the interface will occur unless the normal load on the slider is zero. Theoretically, zero load could be achieved with an air bearing slider if the suspension load balances the air bearing pressure force exactly. However, maintaining a zero load for all operating conditions of a hard disk drive is difficult to accomplish, and no commercial contact recording device has been marketed so far with these attributes.

Several other approaches to contact recording have been proposed in the past. Yeack-Scranton et al (1990) suggested the use of a piezo-electrically supported read/write element on the slider. The read/write head was adjusted so as to be in close proximity to the disk surface only during writing or reading. At other times the flying height was high. Manufacturing concerns stand in the way of implementing this approach in a commercial product.

Figure 7 Thermal flying height control a) heat element 'OFF' b) heat element 'ON'



An alternative "fly low only when needed" approach is available using thermal flying height control, introduced in the latest generation of commercially available hard drives. In this approach, a heater element is located in close proximity to the read/write element of the slider (Figure 7a). If the flying height needs to be reduced, as, for instance, during "read operations", the heat element is energized and thermal expansion of the material surrounding the heat element cause a motion of the adjacent read element to a location closer to the disk surface (Figure 7b). If the reading process is completed, the heat element is turned off and the material cools down. This causes a withdrawal of the read element, resulting in the initial, much higher spacing.

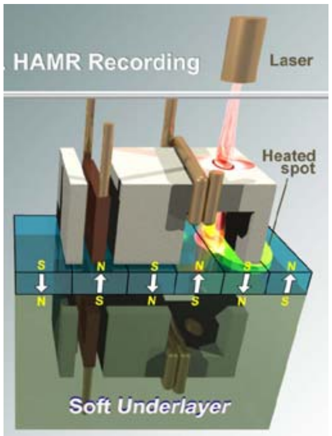
8. HEAT-ASSISTED MAGNETIC RECORDING

At a storage density of 500Gbit/inch^2 (Bertram & Williams, 2000) the so-called super paramagnetic limit is likely to be reached. This limit describes a situation in which the magnetic energy stored within a bit becomes so small that thermal fluctuations can cause the magnetization direction of a bit to change instantaneously, thereby causing the information in a bit to be lost.

To increase the magnetic energy stored in a bit, it is necessary to increase the coercivity of the magnetic material. However, present day magnetic heads cannot write on very high coercivity materials. One solution to this dilemma is to heat the magnetic material above the Curie temperature and write on it during the cooling process when the coercivity is still low. After cooling down to room temperature, the magnetization is "frozen" into the bit cell.

In Figure 8 a schematic of heat assisted magnetic recording is shown. In the case of heat assisted magnetic recording, laser light is used to heat the magnetic material locally, prior to writing. Temperatures on the order of 600 to 700 degrees Centigrade are likely to occur in heat assisted magnetic recording, and severe problems with thermal degradation of the lubricant layer on the disk surface are likely to occur.

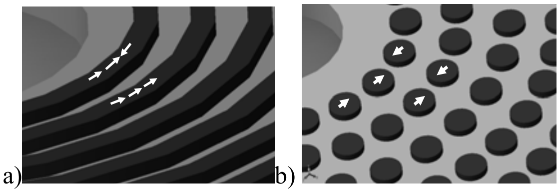
Figure 8 Schematic of Heat Assisted Recording (source: Seagate Technologies)



9. DISCRETE TRACK AND BIT PATTERNED MEDIA RECORDING

Another approach towards achieving ultra high densities in excess of 500Gbit/inch^2 is to partially or completely isolate each magnetic bit from its neighbor, thereby reducing cross talk and transition noise. This so-called "patterned media" approach can be implemented in the form of discrete track recording or discrete bit recording.

Figure 9 a) Discrete Track Recording, b) Bit Patterned Media



In Figure 9a) a schematic of the disk surface for discrete track disks is shown, and in Figure 9b) a bit patterned disk is depicted. In discrete track recording the slider flies over a "grooved" disk surface, for which the width and depth of grooves are on the order of 40 to 100 nm, respectively. In bit patterned recording the slider flies over a surface with pillar-like structures. At a storage density of 1Tbit/inch^2, the single "pillar" like structures have a diameter of approximately 12nm. The numerical simulation of patterned disks using the Reynolds equation requires extremely fine discretization. Considering that typical slider dimensions for femto sliders are 0.7mm times 0.85mm, and that the smallest feature size of a patterned media head/disk interface is on the order of several nanometers, we determine that a viable numerical model would need to have several hundred million degrees of freedom. Models that large cannot be handled on present day computers and further simplification and assumptions have to be made to decrease the model size. Progress towards an understanding of patterned media can be made, however, by considering that the effect of the groove structure on the disk is most important in those areas where the flying height is lowest. Thus, very dense discretization is necessary only at the trailing edge of the slider, while in other areas, where the spacing between slider and disk is large, a much coarser discretization is sufficient.

In Figure 10 the pressure distribution over a typical discrete track disk is shown. For visualization purposes a large groove width of 5µm was used.

Duwensee et al (2006) investigated the effect of different groove depths on the slider steady state flying attitude for a constant groove width to pitch ratio. Figure 11 shows the loss of flying height vs. groove depth for several slider designs. For features smaller than 500nm, the model would become too large to be solved on a single PC. Parallel computing has to be utilized to solve problems of this size, especially if transient phenomena are desired. Molecular dynamics or Discrete Simulation Monte Carlo Techniques appear to be useful methods to study the flow through a nano-sized channel in the case of discrete track recording or around pillar like nano structures of bit patterned media. Mathematical techniques such as mapping (Xiu & Tartakovsky, 2006) or homogenization (Buscaglia & Jai, 2004) are also promising methods for the simulation of the head disk interface and are currently evaluated for patterned media applications.

10. DISCUSSION AND SUMMARY

It is apparent that tribological problems of the head disk interface are key issues in present and future hard disk storage devices. These problems seem to become even more difficult than those in the past. Research on new heat-resistant lubricants as well as new air bearing designs for discrete track and bit patterned media will dominate the research agenda for many years to come.

Figure 10 Pressure distribution of slider flying over DTR media a) entire air bearing surface, b) detail of pressure at trailing edge pad

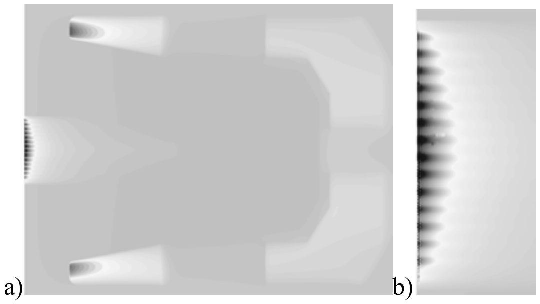
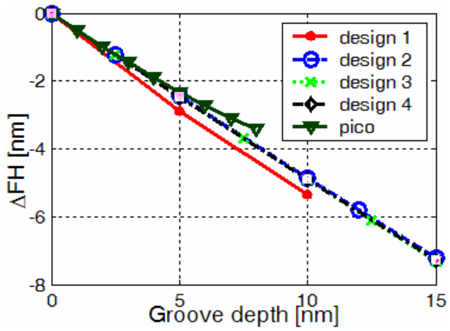


Figure 11 Flying height loss vs. groove depth



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