Interface stability study towards ultra-high density magnetic recording

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Interface Stability Study towards Ultra-High Density Magnetic Recording

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A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Master of Engineering

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ABSTRACT

Information storage technology is the backbone technology of the modern information society. Magnetic disk drive is the major information storage device. One critical challenge for modern magnetic disk drive is the ability to achieve stable and small spacing between the data read/write head and data storage media which allows stable signal to be read and written on the media. This thesis investigates the stability associated with the head-disk interface for future ultra-high density magnetic recording. Currently, the areal density of the top level magnetic disk drives is around 120 Giga-bit per square inch (Gb/in^2). The work reported in this thesis is targeted at the technology required for 1000 Gb/in^2 (or 1 tera-bit per square inch) of areal density and beyond, which requires a head-disk physical spacing or flying height of the head-slider of about 3.5 nm or below. One significance effect of such small spacing is that the short range surface interaction forces such as the intermolecular force, the lubricant-induced meniscus force and the electrostatic force become comparable in magnitude to the slider air bearing force. As a result, the spacing or flying height stability becomes a severe concern.

To design a stable and robust head-disk interface, the various influences and effects of the surface interaction forces need to be understood clearly. Thus, this research work focuses on studying the effects of these forces through a series of experiments. A relative ranking of the three types of surface interaction forces is also conducted through a self-developed experiment. This allows the dominant surface interaction forces to be known which can provide useful information when developing higher density drives. This study of surface interaction forces applies a highly sensitive method known as the harmonic vibration method to achieve accurate experimental

results. This method involves applying controlled amount of electrical voltage across the head-disk interface to create the required electrostatic forces.

Apart from surface interaction forces, slider-lubricant interaction is also another major problem that could affect the stability of the head-disk interface. A method to study slider-lubricant interaction quantitatively is developed for this research work. This method determines the intensity of slider-lubricant interaction by measuring the relative amount of lubricant transferred away from a lubed disk surface. The effect of different air bearing parameters on the intensity of slider-lubricant interaction is identified and a strategy to reduce the intensity of slider-lubricant interaction is proposed in the end. It is found that a smaller trailing pad could effectively reduce the intensity of slider-lubricant interaction. The effect of electrostatic force on the intensity of slider-lubricant interaction is also studied. With increased electrical voltage across the head disk interface, the corresponding amount of lubricant transferred across the head-disk interface increases as well. This increases the intensity of slider-lubricant interaction.

Results of the experiments and analysis conducted showed that to improve the stability of the head-disk interface, a stiffer air bearing slider and a smaller slider trailing pad are recommended as they can reduce the effect of surface interaction forces. Not only that, a smaller trailing pad can also effectively reduce the amount of lubricant transferred across the head-disk interface thus reducing the intensity of slider-lubricant interaction. This will ensure a more robust and stable head-disk interface.

LISTS OF PUBLICATIONS

1. Y. Ma, B. K. Tan and B. Liu, "Lubricant transfer and slider-lubricant interaction at ultra-low flying height," *J Magn. Magn. Mater.*, vol. 303, pp. 110-114, Mar 2006.
2. B. K. Tan, B. Liu, Y. Ma and S. F. Ling, "Effect of Slider Trailing Pad Size on Lubricant Transfer," Digest of *IEEE International Magnetism Conference (Intermag 2006)*, San Diego, California, 8-12 May 2006.
3. B. K. Tan, B. Liu, Y. Ma, M. Zhang and S. F. Ling, "Effect of Electrostatic Force on Slider-Lubricant Interaction," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2241-2243, Jun 2007.

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CHAPTER 1

Introduction to Magnetic Data Storage System

1.1 Evolution of Data Storage System

Magnetic recording technology, represented by magnetic hard disk drives (HDD), has been the most common means of data storage in the modern information society. It is the fundamental storage solution for personal computers and server systems because of its enormous storage capacity. In recent years, magnetic hard disk drives have also been used extensively in consumer electronics products such as the personal media player (PMP), MP3 player, digital video camcorder (DVC), mobile phone, high-definition TV (HDTV), Digital Video recorder (DVR), etc., to store digital information. Thus, HDD has evolved to become a necessity in this modern era.

International Business Machine (IBM) introduced the world's first commercial hard disk drive, the IBM RAMAC 305 in September 1956. RAMAC stood for "Random Access Method of Accounting and Control". It was a fast access data recorder using rigid disks and heads with random access to any data track. It contained a stack of fifty 24-inch diameter aluminum disks coated on both sides with a magnetic iron oxide, with an areal storage density of 2000 bits/in². The read-write head was supported over the disk surface by a hydrostatic pressurized air bearing. The capacity of the entire disk file was 5 million 7-bit characters or 4.4 megabytes (MB), with a

data transfer rate of 70 kbits/s [1]. At that time, IBM 350 disk drive was a revolutionary product because it allowed more storage in less space as compared with magnetic storage drums.

However, the size of those disk drives is huge as shown in Fig 1.1. In today's hard disk drive, its physical size has been shrunk to fit the palm of our hand. Fig. 1.2 shows Hitachi Global Storage Technologies (Hitachi GST) 1 inch Microdrive of physical dimension as small as 42.8 x 36.4 x 5.0 mm.

(a)

(b)

Fig. 1.1. (a) IBM RAMAC 305 in 1956. (b) Closer view of the disks stack..

Alongside the shrinking physical size of the disk drives, the areal density is growing to meet the ever increasing demand of data capacity in this present digital information age. Fig. 1.3 shows that with the introduction of the Magnetoresistive (MR) head in 1991, the rate of areal density growth was accelerated to about 60 % per year. In 1997, this rate was further accelerated to 100 % per year due to the introduction of Giant Magnetoresistive (GMR) head [2]. Through the years, the areal density growth rate has continued to exceed Moore's law which predicts that transistors counts double every 18 months.

Fig. 1.2. Hitachi GST 1 inch Microdrive.

Fig. 1.3. Hitachi GST Areal Density Perspective [2].

Presently, an areal density of 100 Gbit/in² has already been demonstrated [2]. In order to achieve even higher density of 1000 Gbits/in², the magnetic bits have to be made smaller and packed closer. However, when bits are so tiny, they impose a superparamagnetic effect where bits lose their ability to hold their magnetic orientations for an extended period of time (10 years) [3]. This causes data corruption, rendering the storage device unreliable and thus unusable. To overcome this limit, the data recording mechanism has to be switched from the conventional longitudinal recording scheme to a perpendicular recording scheme.

Besides reducing the grain size to achieve higher areal density, extremely low head-disk spacing has to be realized too. This causes the technology to switch from a short range force free scheme to a short range force accounted one. This will pose serious challenges to the head-disk interface researchers.

1.2 Magnetic Hard Disk Drive Technology

Magnetic hard disk drives store data on a continuously spinning disk made of aluminum or glass with a layer of magnetic material coated on both sides of each disk. Data is written to and read from the disks through two separate elements called the read head and the write head. An illustration of the reading and writing process is shown in Fig. 1.4a. The write head consists of a coil wrapping around a ring-shaped electromagnet with a gap at the surface facing the disk [4]. When a current is fed into the head, the magnetic field from the gap magnetizes the disk magnetic medium as shown in Fig. 1.4b. The magnetic field at the gap establishes the polarity of the magnetic medium under the write gap. The smaller the gap length is and the closer the

head is to the disk, the stronger the magnetic field and the higher the possible bit density. The narrower the gap width is, the higher the possible track density. Reversals of the electric current result in magnetic field reversals at the gap, which in turn result in reversals of the polarity on the magnetized media on the disk. These reversals are used to define bits. Since the disk is spinning, magnetic flux reversals or bits are arranged along concentric circles on the disk, called tracks. Fig. 1.5 illustrates the tracks in concentric circle.

The read head is of thin-film and metalized structure. The reading process is based on the magnetoresistive (MR) effect [5]. The MR effect refers to the change in resistivity of metals in the presence of a magnetic field. A small current is sent through the MR head and the change in resistance is sensed when a polarity reversal associated with a bit passes under it. Most modern drives use giant magnetoresistive (GMR) heads which are more sensitive to the magnetic field variation than the standard MR head. The read and write head are integrated into a larger structure called the slider during fabrication process. The slider has many important functions. It is used to hold and position the read-write head in place, relative to each other. It also places the read and write head in close proximity to the magnetic bits by “flying” above the spinning disk. These sliders fly over the disks as a result of the hydrodynamic air bearing that is generated at the head-disk interface by the proper air bearing surface (ABS) design of the slider and the high speed relative motion between the slider and the disk surface.

Fig. 1.4. (a) Illustration of reading and writing process. (b) Schematic of the cross-sectional view showing the magnetic field at the gap [4].

Fig. 1.5. Tracks in concentric circle and positioning of head on desired track [5].

Fig. 1.6. Schematic diagram of a hard disk drive [4].

The slider with an integrated magnetic read and write head, as illustrated in Fig. 1.5, is attached to one end of a suspension as shown schematically in Fig. 1.6. The other end of the suspension is attached to the actuator arm, which is mounted on a ball bearing pivot structure on the drive case. Rotation of the arm about the pivot is driven by a voice coil motor (VCM) composed of wire coils that are attached to the actuator and permanent magnets mounted on the drive case [5]. When an electrical current is passed through the coils, the resulting magnetic field generated by the coils “pushes” against the static magnetic field of the permanent magnets and causes the actuator to rotate about the pivot; thus positioning the read-write head at the desired radial tracks on the disk (refer to Fig. 1.5.).

1.3 Mechanics of Head-disk interface

An areal density of 100Gbit/in² has already been demonstrated [2], and the quest to achieve 1 Tbit/in² and beyond is now the common goal of academic and industry researchers. Research organizations such as Data Storage Institute (DSI), has been working closely with the Information Storage Industry Consortium (INSIC) and other industry partners, to achieve this common goal.

According to the Wallace head-disk spacing loss equation [6], signal loss as the result of such a spacing can be reduced exponentially by reducing the spacing between the read/write head and the magnetic layer of disk-medium. This spacing is called the magnetic spacing as it is the magnetic distance between the head and disk media [7]. Thus, the smallest magnetic signal loss could be obtained at zero spacing. However, zero spacing is impossible due to the existence of disk surface roughness and the requirement of having protective layers to cover both head and disk surfaces - to

prevent possible wear when there is relative motion between the two surfaces. To achieve disk areal density of 1 Tbit/in², a magnetic spacing of 6.5 nm or smaller is required [8].

The magnetic spacing is inclusive of the thickness of the protective overcoat of the slider and the disk surface, the lubricant layer thickness and the physical spacing between the slider and the disk surface. To achieve 1 Tbit/in² of areal density, the physical spacing between the slider and the disk surface has to be reduced to approximately 3.5 nm as illustrated in Fig. 1.7a. Fig. 1.7b shows the change in the physical spacing for IBM-Hitachi GST (Hitachi Global Storage Technologies) hard disk drive over the years. In the process of increasing areal density from 3 Gbit/in² to 35.3 Gbit/in² and then 100 Gbit/in², the corresponding physical spacing (flying height) has been reduced from 38 nm to 10 nm and then 7 nm, respectively [9]. In recent time, a femto slider with a physical spacing of 3.5 nm has been developed by researchers in Data Storage Institute (DSI). Their work won them the Singapore National Technology Award (NTA) and the Technical Achievement Award of Information Storage Industry Consortium (INSIC) in year 2005.

Over the years, the use of a self-pressurized ceramic slider remains the fundamental way to provide a reliable interface at a controlled spacing between the slider and the disk surface. In addition to providing this controlled spacing, the design of the components of the head-disk interface must provide years of operation including thousands of drive starts/stop cycles. This involves optimizing the disk roughness and waviness; the thin Diamond-like-coating (DLC) on the disk and slider surfaces which provides wear resistance and more importantly corrosion protection of the magnetic

media and the slider; and the molecularly thin lubricant layer above the DLC which reduces wear and friction of the head disk interface [9].

Table 1.1

Magnetic and physical spacing for 1 Tbits/in² of areal density.

Fig. 1.7. IBM-Hitachi GST drive's Physical Spacing over the years [9].

1.4 Air bearing slider

The air bearing slider is of critical importance to the success of a robust and high capacity disk drive. The slider flying height is controlled passively through self-bearing sliders. The slider surface that faces the disk is known as the air bearing surface (ABS) as the air-bearing is formed between this surface and disk surface. The air bearing surface is shaped and patterned like the example shown in Fig. 1.8. Fig. 1.9 illustrates the working process of an air bearing slider. As the disk rotates, the boundary layer of air next to the disk surface moves at the same velocity as the rotating disk. When it moves into the gap between the slider and the disk surfaces, this boundary layer of air is compressed and the high pressure between the slider and the disk surfaces provides gas lubrication and lifts the slider up,

Fig. 1.8. Actual air bearing surface (ABS) of a slider [10].

Fig. 1.9. Schematic of a slider flying over disk.

The slider body is supported by the gimbal and suspension is schematically illustrated in Fig 1.9. The gimbal acts as a flexible support of the slider to the suspension which allows the slider to stay close to the surface despite undulations and asperities of the disk surface. The suspension supplies a load, known as the gram load, to the slider, which counter balances the upward aerodynamic forces of the air bearing that cause the slider to "take off" from the disk surface [5]. The "flying" slider has 3 degree-of-freedom, i.e., vertical, pitch and roll direction. The flying attitude and characteristics of the slider are complex functions of many parameters such as the shape of slider air bearing surface, the slider's gram-load, the slider's pitch/roll/skew angle and the disk linear velocity. A numerical solution of this complex flying characteristic can be obtained through air-bearing simulation program by applying the generalized Reynolds equation.

High dynamic performance requires high dynamic response speed and frequency. Therefore, smaller slider size and mass is required. Fig. 1.10 shows the evolution of the slider form factor (slider dimension) from year 1980 to 2003. The reduced slider size improves the response of the slider to disk waviness, thus reducing the flying height variation of the slider in the disk drive. The combined slider and suspension mass reduction also improves shock resistance, reduces power consumption and improves disk storage capacity. Not only that, this reduced size will also allow the slider to fly closer to the disk thus reducing Wallace's Spacing Loss and increasing the density of hard disk drives.

Another benefit of reducing the slider size is the manufacturing efficiency. Smaller slider size means that more slider can be fabricated from a wafer with the same size.

By placing more sliders on a wafer, wafer productivity for the slider manufacturer is significantly improved and manufacturing costs reduced [10].

Table 1.2

Evolution of slider form factor [10].

Slider Size	Mini 100%	Micro 70%	Positive Pressure Nano 62%	Negative Pressure Nano 50%	Pico 30%	Femto 20%
Intro Year	1980	1986	1991	1994	1997	2003
Dimensions, mm						
Length	4.00	2.80	2.50	2.00	1.25	0.85
Width	3.20	2.24	1.70	1.60	1.00	0.70
Height	0.86	0.60	0.43	0.43	0.30	0.23

Air bearing design is becoming more complicated as the slider's physical dimensions becomes smaller to enable lower flying height, better shock resistance, lower power consumption, higher areal density etc. In the past, short range surface interaction forces such as the intermolecular force, the lubricant-induced meniscus force and the electrostatic force have negligible effect on the higher "flying" slider (>20 nm). They are therefore not taken into account when designing the slider. However, the present slider is flying at less than 10 nm of physical spacing between the head and the disk and shock/vibration can further lower the physical spacing to less than 5 nm. As a result, these short range surface forces have to be taken into account when designing the slider air bearing surface. Therefore, the understanding of the slider dynamics under the effect of these surface forces becomes a crucial aspect in developing a reliable head-disk interface.

1.5 Problem statement, challenges and objective

High density data storage requires further reduction of the flying height whilst retaining or improving the robustness of head-disk systems. The challenges of future hard disk drive design involve designing a tribologically reliable head-disk interface for an ultra-high density magnetic storage system. To achieve 1 Tbit/in² of areal density, it is projected that the targeted magnetic spacing should be reduced to a level of around 6~7 nm, including 1.5 nm slider overcoat thickness, 2.5~3 nm of flying height clearance between slider head and disk surfaces, 1.5 nm of disk overcoat thickness and 1~1.2 nm of lubricant thickness [11]. The greatest challenge involves realizing robustly a 2.5~3 nm stable physical clearance between the slider and the disk irregardless whether the disk drive operates under normal or harsh environmental conditions.

To further complicate matters under such physical constraints, surface interaction forces such as the intermolecular force, the lubricant-induced-meniscus force and the electrostatic force become comparable with the slider's air bearing force. These forces, which are attractive in nature, will attract the slider towards the disk and may crash with the disk, leading to severe contact vibration. As a result, the stability and robustness of the head-disk system will be affected. In other words, solutions must be introduced to reduce the effects caused by the short-range surface interaction forces. In addition, when the disk overcoat and lubricant becomes essentially thin, any contact between the slider and the disk might damage such overcoat and expose the magnetic layer underneath. This may cause data corruption on the disk media and may also lead to damage of the read/write head. Another major challenge for this study involves fabricating a disk of very low surface roughness and gliding height to

support the low flying height slider. The commercially available disk gliding height is not low enough for the study of future head-disk systems. Therefore, special disk processing technique such as burnishing has to be performed on the disk in order to reduce the gliding height for the specialized needs of research work and future production.

The objective of this research is to study the head-disk-interface stability for ultra high density recording. Two main problems that affect the head-disk-interface stability are surface interaction forces and slider-lubricant interaction. To design a stable and robust head-disk interface, the various influences and effects of the surface interaction forces and slider-lubricant interaction need to be understood clearly. It is also important to know which surface interaction forces has the strongest effect on the stability of the head-disk interface. By knowing the dominant surface interaction force, attention can then be focused on it to effectively reduce it, thus, improving the overall stability of the head-disk interface. Therefore, it will be beneficial to do a relative ranking of these surface interaction forces.

Apart from the stability problem associated with the surface interaction forces, slider-lubricant interaction is also a major concern. The slider-lubricant intensity can be affected by various parameters such as the slider air bearing design and the amount of electrostatic force present at the head-disk interface. The effect of these parameters on the intensity of slider-lubricant interaction will be studied experimentally. Strategies will be proposed to reduce the intensity of slider-lubricant interaction.

1.6 Thesis structure

This thesis includes seven chapters. The first chapter is an introduction to the magnetic data storage system. It explains the fundamental principles of head-disk interface and air-bearing slider. The thesis problem statement and objective of this research are also presented in this chapter.

Chapter 2 compiles all the literature reviews of the recent progress on the study of low flying height technology and the corresponding slider-disk interaction issues. The effects of surface interaction forces such as the intermolecular force, the lubricant-induced meniscus force and the electrostatic force on stability of head-disk interface are also presented.

Chapter 3 gives an insight into the experimental setup and modeling of the platform. It explains the testing methodology adopted and the sample fabrication/ preparation process. Chapter 4 presents the experimental results of the surface interaction forces studies and relative ranking of these forces. In chapter 5, the slider-lubricant interaction and some approaches towards stable head-disk interface are explained. The lubricant transferring phenomena with different slider designs are explored in this chapter too. Chapter 6 further examines the issues of chapter 5. The effect of electrostatic forces on lubricant transferring is explored by applying different interface potential across the slider-disk system to create different levels of electrostatic force.

Chapter 7 summarizes and concludes all the results obtained in this research work. In addition, there will be recommendations to improve the stability of the head-disk interface and proposals for possible future research activities in this final chapter.

CHAPTER 2

Literature review on the stability of head-disk interface

2.0 Introduction

As the head-disk spacing of the hard disk drive becomes smaller, the effect of short range surface interaction forces that are previously negligible becomes an important issue to consider. These surface interaction forces include the electrostatic force, the lubricant-induced meniscus force and the intermolecular force. Such forces can cause severe dynamic instability especially when the head-disk spacing becomes smaller than 4~5 nm. These interactions, which are mainly adhesive in nature, tend to attract the flying slider towards the disk surface and may lead to head crash and render hard disk drive failure.

When the areal density of hard disk drive approaches 1 Tbit/sq², it is expected that the flying height between the slider and the disk will be reduced to about 2.5~3.5 nm in order to maintain the magnetic signal-to-noise ratio (SNR) requirement. When the flying height is reduced to such a range, the surface interaction forces become comparable in magnitude to the slider's air bearing force. When this happens, the slider's air bearing force can no longer maintain a stable flying slider when surface interaction forces act upon the slider-disk interface. The smaller the head-disk spacing is, the stronger the surface interaction forces. When the surface interaction forces are

greater than the slider's air bearing force, they will pull the slider downward and lead to a reduced slider-disk spacing. Reduced spacing will further increase the surface interaction forces and further drag slider towards disk surface till contact happens. Therefore, in this chapter, effort has been made to investigate the interaction forces that exist in head-disk interface in order to fully understand their influence on head-disk interface's stability.

2.1 Intermolecular force, flying height hysteresis and interface stability

Intermolecular forces are electromagnetic forces that act between molecules or between widely separated regions of a macromolecule. The van der Waals force is one of the intermolecular forces that has significant effect on the stability of head-disk interface when the flying height is below 4~5 nm. This force involves the attraction between temporarily induced dipoles in non-polar molecules which often disappear within an instant. This polarization can be induced either by a polar molecule or by the repulsion of negatively charged electron clouds in non-polar molecules.

Presently, many journals use modeling, computer simulation or an indirect experiment to quantify the effect of intermolecular force on the stability of the head-disk interface [12, 13]. Li *et al* [12] investigated the effect of intermolecular force on a deep sub-10 nm flying height slider. Based on their simulation results, the intermolecular forces strongly attract the slider toward the disk when the clearance between the slider and disk becomes very small (<10 nm). Thronton and Boggy *et al* [13] had shown experimentally that a slider can change suddenly from stable to unstable proximity flying due to the effect of intermolecular force. In their experiment, "touch down" and

“take off” operation were conducted. This operation involved reducing the velocity of the disk to effectively reduce the slider-disk spacing. When the upward air bearing force acting on the slider can no longer support the gram load force applied by the suspension, contact between the slider and disk surface will occur. The velocity at this point is known as the touch down velocity. After “touch down”, the velocity of the disk is increased to a point where the slider gain enough air bearing force and breaks contact with the disk surface. The velocity at this point is known as the take off velocity. The difference between the take off velocity and touch down velocity is known as flying height hysteresis. As observed in their experiments, higher velocity was required for the slider to “take off” or break contact from the disk after the slider touched down. The observed flying height hysteresis in the experiment, slider-intermittent instabilities and “snapping” from stable to unstable proximity flying were also shown to be caused by intermolecular force effect.

In a recent paper by Ambekar and Bogoy [14], factors affecting the touch down and take off velocity had been further investigated based on their domain of operations. In their test, it was found that touch down velocity decreased when there was an increased in lubricant thickness. This trend opposed the one predicated by the meniscus forces as thicker lubricant leads to stronger meniscus force and, therefore, increased touch down velocity. Multilayer modeling of intermolecular force explained this trend and thus, it had been concluded that intermolecular forces influenced the touch down velocity and the slider dynamics at close proximity [15]. When more lubricant is allowed to accumulate on the slider surface (the case of thicker lubricant), take off velocity tend to increase. This is due to the meniscus forces that act through lubricant mediated adhesion. A rough or contaminated disk is also found to cause

early touch down but with burnishing during contact, the slider can regain its stability [16]. Therefore, it is concluded that the intermolecular force and meniscus force are the contributing factors to flying height hysteresis, which are also influenced by disk topography and slider dynamics.

In another paper by Tagawa *et al* [17], the effects of ultra-thin lubricant films on slider flying height hysteresis behaviour had been investigated. The flying height hysteresis for a disk lubed with a novel A20H lubricant was found to be greater than the flying height hysteresis of a disk lubed with conventional Z-DOL lubricant. This is because A20H lubricant layer on the disk surface has a stronger interaction with the slider's protective overcoat layer (known as Diamond-Like-Carbon overcoat) during the slider-disk contact than the Z-DOL lubricant layer. Therefore, disk lubed with A20H lubricant has a higher tendency to prevent the slider from taking off when compared with a disk lubed with Z-DOL lubricant. The magnitude of slider vibration during contact for the Z-DOL was also found to be smaller than the A20H's. It is because Z-DOL lubricant has a higher mobility than A20H lubricant which has better slider vibration suppression during event of any slider-disk contact [18].

2.2 Functional lubricant and interface stability

Beside the intermolecular force, thin film lubricant on disk surface also plays a very important role in determining the reliability of the head-disk interface. Generally, a molecularly thin layer of lubricant such as perfluoropolyether (PFPE) is applied to the diamond like carbon (DLC) overcoat to protect the disk surface and improve the tribological performance of magnetic disks. This lubricant layer consists of a "mobile" portion and an "immobile" (bonded) portion [19]. As the lubricant thickness

increases, the replenishment rate also increases due to the increased amount of mobile lubricant. The replenishment rate refers to how rapid the mobile lubricant can cover the depleted lubricant track if it exists. Lubricant thickness can also influence the amount of slider wear. Typically, the thicker the lubricant, the less the slider wear [19]. However, a thick lubricant layer on the disk surface may cause problems as well. If the lubricant gets too thick, it will cause high static friction, high “fly stiction”, higher disk glide avalanche and possibly large vibrations of the slider when flying close to the disk [19, 20]. “Fly stiction” is a commonly observed phenomenon during the Contact-Start-Stop (CSS) operation. The slider, initially at rest, sits on the lubricant layer on top of the disk. Lubricant molecules will migrate around the contacting asperities to form menisci. When the disk rotates, the menisci around the contacting asperities will tend to “stick” the slider to the disk, thus preventing the disk from rotating. This adhesive force is known as the stiction force which might detach the slider from the suspension if it is too strong.

Suh and Polycarpou [20] investigated the relationship between the thickness of molecularly thin lubricant, and lubricant surface roughness of magnetic disks. They observed that as lubricant thickness increased, the roughness amplitude increased too. In their paper, a continuum-based adhesion model based on the Lennard-Jones intermolecular potential was used to estimate the magnitude of adhesion forces with respect to increasing lubricant thickness. The adhesion model simulations showed that for very small slider-disk spacing (1~3 nm), the total adhesive forces were the largest for the roughest disk with the thickest lubricant and smallest for the smoothest disk with the thinnest lubricant. The impact of lubricant film thickness on slider-disk spacing was also investigated by Waltman *et al* [21]. In their experiment, the slider

was first unloaded onto the disk at a high velocity of 6000 rpm. Five seconds later, the disk velocity was linearly reduced to 2000 rpm and allowed the slider to contact the disk surface (touch down) in the next five seconds. The Acoustic Emission (AE) and friction force were monitored during this process to monitor the slider-disk interferences. This experiment was repeated under the same conditions, except with different lubricant thickness. It was found that when lubricant thickness was reduced, the slider-disk interferences started to appear only at a lower disk velocity, i.e. “contact” occurred at a smaller air bearing force or a smaller slider-disk spacing.

Zhu *et al* [22] investigated the effect of lubricant thickness on the head-disk interface dynamics of the stiction-free slider with super-smooth disk surface. Flying height variation and AE signal were measured experimentally during the Contact-Start-Stop (CSS) operation. It was found that thicker lubricant corresponded to a harder slider bouncing and a stronger slider-disk contact. It was also noted that as the lubricant thickness increased, the take off velocity of the disk increased too. This is because thicker lubricant causes larger dynamic meniscus force and viscous shear forces. In a paper by Deoras and Talke [23], dynamics of slider was investigated as a function of lubricant thickness using the Laser Doppler Vibrometer (LDV) instrumentation. The sliders used in the experiment had a nominal flying height of 7 nm flying at a rotational speed of 7200 rpm. The laser spot from the LDV was focused onto the back part of the slider body (the gimbal) to acquire the slider response. Disks with different lubricant thickness were used in this study. The vertical velocity of the slider as a function of the lubricant thickness was monitored. It was observed that the slider vertical velocity increased as the lubricant thickness increased. In addition, the LDV signal showed multiple regions of high slider disturbances corresponding to high

slider velocity. The duration of these disturbances increased with thicker lubricant. This increased in slider vibration was possibly related to an increased in meniscus interaction between the slider-disk interface.

2.3 Electrostatic Force and interface stability

As the slider flies over the disk at small slider-disk spacing, intermittent slider-disk contacts are unavoidable and this causes the tribo-charge/emission phenomenon [24, 25]. Zhu *et al* [24] had studied the effects of lubricant, carbon overcoats and relative humidity on tribocharging at the head-disk interface. They found that the tribocharging increased with the severity increased of head-disk interactions and decreased with the conductivity of the carbon overcoat layer on the magnetic disk. Though the electrostatic forces do not have a significant effect on the flying characteristics of high-flying sliders, they become one of the major concerns for current sliders with low head-disk spacing [26]. These forces are attractive in nature and will cause reduction in the slider flying height [27]. Kiely and Hsia [28] suggested that the electrical charge at the head-disk interface came from two major processes: the transfer of electrons through contact potential or surface potential difference, and the transfer of material through wear-induced tribo-emissions. The contact potential is the potential difference between two plates in the absence of an applied voltage and originates from the plates, which are made of material with different work functions [29]. Knigge *et al* [29] showed that even if the slider and disk were both grounded, a potential difference can exist between them due to the contact potential which generates an electrostatic force greater than van der Waals force.

2.4 Surface interaction forces and relative ranking

With the decrease in the slider-flying height to a level below 3~5 nm, the contribution of surface interaction forces to the total force acting on the slider can no longer be neglected. It would be important to study the influence of these forces quantitatively on the head-disk interface stability. There are two main viewpoints from some of the head-disk interfaces researchers on the dominant surface interaction force. One viewpoint from Mate *et al* [30] suggested that lubricant-induced meniscus force was the dominant adhesive forces that originated from menisci forming around the low flying portions of the slider air-bearing-surfaces. Another viewpoint by Thronton *et al* [31] suggested that the main dominant surface interaction force was not the meniscus force but the intermolecular force. They explained that because the lubricant layer were generally very thin, only a fraction of the lubricant layer was available to behave as a liquid, making meniscus effect energetically difficult to form. Also, according to a kinetic meniscus formation model [32], on the time scale of interest for “bouncing” or unstable proximity of the air-bearing-slider, the liquid volume required to form the meniscus did not have enough time to be transported and was far from the equilibrium state. Therefore, to determine which surface interaction force dominates, a carefully designed experimental methodology has to be developed to study and compare these surface interaction forces.

CHAPTER 3

Experimental methodologies and establishment of platform

3.1 Experimental methodologies and approaches

Presently, the common method to study surface interaction forces is through the slider touch down and take off operation. This method involves reducing the velocity of the disk gradually to effectively lower the slider flying height until it contacts the disk surface (touch down). Stronger interaction force will tend to cause earlier slider touch down, i.e. higher touch down velocity, as compared to having no interaction force. Once the slider has touched down, the velocity of the disk is increased till sufficient air bearing force lifts the slider. The difference between the touch down and take off velocity is usually calculated to determine the level of interaction force. This is known as flying height hysteresis. The larger the flying height hysteresis, the larger the interaction force and vice versa. However, this method has its limit, because every time the slider contacts the disk, debris may form and lubricant may be transferred to the slider.

Another method proposed is to measure the local air bearing frequencies of the slider since air bearing stiffness is related to its resonating frequencies. This is done by focusing a laser spot from the Laser Doppler Vibrometer (LDV) instrumentation onto the trailing edge of the slider. However, the differences of air bearing frequencies

under different interaction forces are too small to be detected by the LDV. Thus, it is difficult to determine the effect of surface interaction forces through this method.

Previously, a method known as the Harmonic Vibration method has been used by B E. Knigge *et al* [29] to study the contact potential between the slider and disk surface. Instead of just using this Harmonic Vibration method to study contact potential only, the author and the team further improve this method to determine the effect of the surface interaction forces which is shown in section 3.2.2. This method is highly sensitive and stable. It involves applying an ac and dc voltage into the head-disk system. Slider harmonic vibrations are monitored by focusing a laser spot from the LDV onto the back of the slider. The harmonic vibration magnitude is a good indication of the intensity of the short range surface interaction between the slider and disk surfaces. A detailed explanation of this method will be presented in the following section.

3.2 Fundamentals of harmonic vibration analysis

3.2.1 Modeling of electrostatic force across slider-disk interface

When an externally applied voltage is applied across a slider-disk interface, an attractive electrostatic force exists between them. To illustrate how the attractive electrostatic force depends on the applied voltage and other physical parameters of a slider-disk interface, a simplified model consisting of the electrostatic force, F_{el} that acts between the two parallel conducting plates is used. This is schematically illustrated in Fig. 3.1. The electrostatic force can then be expressed as

$$F_{el} = V^2 \frac{\epsilon_0 \epsilon_r A}{2h^2} \quad (3.1)$$

where ε_0 and ε_r are the dielectric permeability of free space (vacuum) and air respectively; A the plate area, h their separation distance between the two plates, and V the potential difference between the two plates. In an actual slider-disk interface, the slider is flying at a pitch angle φ . It can be modeled by having a top plate inclined at an angle φ as schematically illustrated in Fig. 3.2. In Fig 3.2, x is the horizontal distance across the inclined and horizontal plate that electrical field is applied on and h is the spacing between the two plates. The spacing h can be expressed as a function of x ,

$$h - h_1 = x \tan \varphi; \quad h = x \tan \varphi + h_1 \quad (3.2)$$

Fig. 3.1. Applied voltage across two parallel conducting plates.

Fig. 3.2. Applied voltage across an inclined plate and horizontal conducting plate.

To determine the electrostatic force across the inclined plate and horizontal plate, the change of electrostatic force dF_{el} with respect to an infinitesimal distance dx is first considered,

$$\frac{dF_{el}}{dx} = \frac{dF_{el}}{dh} * \frac{dh}{dx} \quad (3.3)$$

Where

$$\frac{dF_{el}}{dh} = \frac{d}{dh} \left(\frac{V^2 \epsilon_o \epsilon_r A}{2h^2} \right) \quad (3.4)$$

Surface area $A = xw$, where x is the horizontal distance and w is the width of slider.

Thus, by substituting (3.2) and $A = xw$ into (3.4), equation (3.4) becomes,

$$\frac{dF_{el}}{dh} = \frac{d}{dh} \left(\frac{V^2 \epsilon_o \epsilon_r xw}{2h^2} \right) = \frac{-V^2 \epsilon_o \epsilon_r xw}{h^3} = \frac{-V^2 \epsilon_o \epsilon_r xw}{(x \tan \phi + h_1)^3} \quad (3.4a)$$

By applying equation (3.2), the derivative of h with respect to x is,

$$\frac{dh}{dx} = \frac{d}{dx} (x \tan \phi + h_1) = \tan \phi \quad (3.5)$$

Substituting equation (3.4a) and (3.5) into equation (3.3) gives,

$$\frac{dF_{el}}{dx} = \frac{-V^2 \epsilon_o \epsilon_r xw}{(x \tan \phi + h_1)^3} * \tan \phi = \frac{-V^2 \epsilon_o \epsilon_r xw \tan \phi}{(x \tan \phi + h_1)^3} \quad (3.6)$$

Therefore, the electrostatic force, F_{el} can be determined by integrating equation (3.6) with respect to x ,

$$F_{el} = \int_{x_1}^{x_2} \frac{dF_{el}}{dx} dx = \int_{x_1}^{x_2} \frac{-V^2 \epsilon_o \epsilon_r xw \tan \phi}{(x \tan \phi + h_1)^3} dx = -V^2 \epsilon_o \epsilon_r w \tan \phi \int_{x_1}^{x_2} \frac{x}{(x \tan \phi + h_1)^3} dx \quad (3.7)$$

For simplification purpose, let K_x be $\int_{x_1}^{x_2} \frac{x}{(x \tan \varphi + h_1)^3} dx$ and therefore electrostatic

force equation for inclined plate becomes

$$F_{el} = -V^2 K_x \epsilon_o \epsilon_r w \tan \varphi \quad (3.8)$$

The interface potential difference V between the plates is the sum of two components: an externally applied voltage V_e and an internal contact potential V_{con} . The contact potential is the potential difference between the two plates in the absence of an applied voltage and originates from the plates being made of different work function [29]. In a typical slider-disk interface, the conducting part of the slider body is the Al_2O_3 -TiC (slider main body material) and the conducting part of the disk is the magnetic layer. The Diamond-Like-Carbon (DLC) overcoats and lubricants that are deposited on them, for tribological protection purposes, further modify the work functions of these materials.

If one plate is grounded and the other plate is applied with an external voltage V_e which consists of both dc and ac component, i.e. $V_e = V_{dc} + V_{ac} \sin(\omega t)$, the total interface potential will therefore be $V = V_{con} + V_{dc} + V_{ac} \sin(\omega t)$, where ω is the fundamental frequency of the applied sine wave. The expression for electrostatic force can be rewritten as:

$$F_{el} = -K_x \epsilon_o \epsilon_r w \tan \varphi * (V_{con} + V_{dc} + V_{ac} \sin \omega t)^2 \quad (3.9)$$

After some manipulation, equation (3.9) becomes

$$F_{el} = \frac{-K_x \epsilon_o \epsilon_r w \tan \varphi}{2} * [2(V_{dc} + V_{con})^2 + V_{ac}^2 + 4V_{ac}(V_{con} + V_{dc}) \sin \omega t - V_{ac}^2 \cos 2\omega t] \quad (3.10)$$

In equation (3.10), the first and second term in the square bracket represent the dc response to the applied voltage; the third and the last term in the square bracket represent the first and second harmonic response; respectively. Notice that the first harmonic term becomes zero when the applied dc voltage cancels the contact potential ($V_{dc} = -V_{con}$), implying that the contact voltage can be detected by monitoring the first harmonic signal. The second harmonic term, however, is independent of the applied dc voltage. When $V_{dc} = -V_{con}$, equation (3.10) is further simplified and becomes,

$$F_{el} = \frac{-K_x \epsilon_o \epsilon_r w \tan \varphi}{2} * [V_{ac}^2 - V_{ac}^2 \cos 2\omega t] \quad (3.11)$$

3.2.2 Modeling of slider vibration under externally applied voltage

A two degree of freedom (DOF) spring, mass and damper mechanical system is used to model the slider-disk interface with suspension loading under the influence of the electrostatic force. This is schematically illustrated in Fig. 3.3. The suspension loading effect can be neglected in the modeling as the slider air bearing stiffness, k is much greater the suspension stiffness, k_{sus} by approximately 100,000 times. Therefore, the two DOF mechanical system can be simplified to a single DOF system as illustrated in Fig. 3.4. An externally applied voltage ($V_e = V_{dc} + V_{ac} \sin(\omega t)$) together with the internal contact potential V_{con} at the slider-disk interface will create an electrostatic force, F_{el} . Therefore, displacement of slider z can be determined by solving the following second order ordinary differential equation,

$$m \frac{d^2 z}{dt^2} + c \frac{dz}{dt} + kz = F_{el} \quad (3.12)$$

where z is the vertical slider displacement, m is the mass of the slider, k and c are the stiffness and damping constants on the air bearing surface.

Fig. 3.3. Two DOF model of a head-disk interface with suspension loading.

Fig. 3.4. Simplified single DOF model of a head-disk interface under electrostatic force.

If dc voltage V_{dc} is adjusted to a value such that the first harmonic vibration response become zero, this dc voltage V_{dc} will equate to the negative of the interface contact potential value V_{dc} , i.e., $V_{dc} = -V_{con}$. When this happens, equation (3.11) can be substituted into equation (3.12) and expressed as

$$m \frac{d^2 z}{dt^2} + c \frac{dz}{dt} + kz = \frac{-K_x \epsilon_o \epsilon_r w \tan \varphi}{2} * [V_{ac}^2 - V_{ac}^2 \cos 2\omega t] \quad (3.13)$$

By solving this second order ordinary differential equation (3.13), the slider vertical displacement will be expressed as

$$z = \frac{-K_x \epsilon_o \epsilon_r w \tan \varphi * V_{ac}^2}{2k} \left[1 - \frac{\cos(2\omega t + \varphi)}{(1 - \frac{4m\omega^2}{k}) \cos \varphi - \frac{2\omega c}{k} \sin \varphi} \right]$$

$$z = \frac{-K_x \epsilon_o \epsilon_r w \tan \varphi * V_{ac}^2}{2k} - \frac{-K_x \epsilon_o \epsilon_r w \tan \varphi * V_{ac}^2}{2k} * \frac{\cos(2\omega t + \varphi)}{(1 - \frac{4m\omega^2}{k}) \cos \varphi - \frac{2\omega c}{k} \sin \varphi}$$

$$\text{where } \varphi = \tan^{-1} \frac{1}{\frac{k}{2\omega c} - \frac{m}{c}} \quad (3.14)$$

From equation (3.14), it is obvious that the second harmonic response is independent of the applied dc voltage V_{dc} and the internal contact potential V_{con} . Under a fixed ac driving frequency ω , the amplitude of the second harmonic vibration is dependent on the applied ac voltage V_{ac} , the stiffness k and damping constant c of the head-disk system. If the applied ac voltage V_{ac} is not too large, the amplitude of the second harmonic vibration, i.e., the slider displacement z , should be linear with V_{ac}^2 . Therefore, if the graph of second harmonic vibration amplitude (z) against V_{ac}^2 is plotted, the gradient of the line will be related to the stiffness k and damping c of the

head disk interface. Thus, by analyzing the gradient of the displacement versus applied ac voltage curve, information about the stiffness of the head disk interface could be obtained. This will allow different level of short range surface interaction forces to be determined since they are related to the stiffness of the head disk interface.

3.3 Establishment of experimental platform

3.3.1 Experimental composition

The harmonic vibration method that is shown in section 3.1 is used to determine the effect of surface interaction forces. To apply the harmonic vibration method, an experimental platform is designed and setup as schematically illustrated in Fig. 3.5.

Fig. 3.5. Schematic illustration of experimental setup.

The experimental platform composes of four main parts:

1) Head-disk Testing Stand (Guzik Spinstand)

A head-disk testing stand as shown in Fig. 3.6 is used for the reading, writing and testing of the magnetic signal of a magnetic disk. In this experiment, it is used mainly for the following purposes: loading and unloading of a slider onto disk surface; precise positioning of the slider to the expected testing track and keeping the slider at that track precisely; flying of the slider in nanometer spacing over the disk and controlling the rotation speed of disk.

Fig. 3.6. Head-disk testing stand (Guzik Spinstand).

2) Capturing slider vibration response using Digital Laser Doppler Vibrometer

The slider vibration response when subjected to an externally applied ac voltage has to be measured accurately in order to determine the effect of surface interaction forces. There are generally two main types of vibration measuring methods that can be used for this experiment. They are the contacting and non-contacting measurement methods. The contacting measurement method typically uses a sensor such as an accelerometer to capture the vibration response of the slider. However, the accelerometer is too big to be attached onto a millimeter sized slider (the slider used in this experiment has a physical dimension of only 1.25 mm x 1.0 mm x 0.3 mm

which is too small for the accelerometer to be attached on). In addition, the sensor mass cannot be neglected because it is comparable to the slider mass. Attaching the sensor will alter the vibration response of the slider and cause inaccurate measurement. Therefore, a non-contact measurement method is preferred.

A widely adopted non-contact measurement method used to capture the slider vibration responses is the Laser Doppler Vibrometer (LDV) method. The LDV can also detect those very high frequency components (up to 20 MHz) to be measured. A laser spot emitted from LDV is focused at the back of the slider surface to measure the slider vibration response. The captured signal is input into a computer acquisition system that is capable of performing various type of data analysis including Fast Fourier Transform (FFT).

Basically, LDV uses Doppler effect to measure displacement and vibration. The light scattered from a moving object such as a slider, will be shifted in frequency and this shifting is proportional to the velocity of the object, i.e., the Doppler effect. Fig. 3.7 shows the schematic of the optical components inside a LDV. Within the LDV, a high precision interferometer detects the frequency shift of the laser light. To achieve this, the interferometer splits the light into reference beam and an object beam. The reference beam is focused directly onto the photodetector. The object beam is incident onto the back of the slider where the light is scattered by the moving slider. Depending on the velocity and displacement of the moving slider, the backscattered light changes in frequency and phase. The characteristic of the motion is completely contained in the back scattered light. When the backscattered light is combined with the reference beam, it creates a modulated detector output signal, revealing the

Doppler shift frequency. This frequency shift is directly proportional to the velocity and displacement of the slider. Further signal processing and analysis will provide the vibration velocity and displacement of the slider [34]. The digital LDV system used in the experiment has an output level of 50 nm/V for 50 Ω resistance setup and 25 nm/V for high impedance setup. The input impedance of Junction box VDD-Z-011 is 1 M Ω . Its lower cutoff frequency typically is 25 kHz (-3dB), and upper cutoff frequency is 24MHz (-3dB).

Fig. 3.7. LDV optical components [34].

3) Contact detection using Acoustic Emission (AE) sensor

When the slider flies over the disk surface at low flying height (<5nm), contact between the slider and disk asperities may happen. Therefore, it is important to determine if there is any contact during the experiment. Acoustic Emission (AE) sensor is used to detect contact between the head-slider and disk surface. This AE sensor is attached onto a head-gimbal-assembly (HGA) jig which is near to the end of the suspension. Acoustic Emission may be defined as a transient elastic wave generated by the rapid release of energy within a material [33]. In general, AE is a stress wave that can be generated by bending, torsion, crack formation and contact

between two surfaces. These stress waves are subjected to wave propagation phenomena such as dispersion and reflection from boundaries.

4) External voltage supplier

Continuously voltage source into the head-disk interface is supplied by an external voltage supplier. It will then create an interface potential difference between the slider and the disk surfaces. The applied voltage consists of an ac and dc components. The frequency of the input ac voltage can be adjusted to suit the test requirements. Different types of ac voltage source such as, sine wave, square wave, random signal, white noise, burst random signal, etc., can be applied to the head-disk interface to simulate different interface conditions. In this study, only sine wave signal is used.

3.3.2 Experimental platform establishment

The actual experimental setup is shown in Fig. 3.8. During the set up of the experimental platform, special considerations of the following issues have to be made:

1) Vibration isolation

Environmental vibration can cause unwanted noise signal generation in the test results. It is therefore important to isolate these unwanted environmental vibration signals. To isolate those disturbances, the whole head-disk testing stand is placed onto a vibration isolated platform such as the one shown in Fig. 3.8, to minimize the environmental vibration disturbance. The author noticed that is also important to have a vibration isolation platform for achieving repeatable results.

2) Grounding and electrical insulation

Grounding of the head-disk testing stand at suitable positions is important. It reduces electrical noise from a level of more than 100 mV to less than 50 mV in the applied voltage. Furthermore, the head-disk testing stand is electrically insulated from the vibration isolation table by placing a rubber mat in between them. This will prevent any transfer of electrical charge between the stainless steel platform and the head-disk testing stand.

3) Acoustic emission sensor insulation

Acoustic emission sensor is electrically isolated when a very thin electrical insulation layer is placed between the acoustic emission sensor and the HGA jig surface. This can reduce the high noise signal captured by the Acoustic Emission sensor even when the slider is not flying over the disk.

Fig. 3.8. (a) Overall experimental setup. (b) Enlarged view of the testing system.

3.4 Preparation of disks for experimental tests

The disks used in this experimental study of short range surface interactions include high end commercial disks manufactured by Showa Denko (SDK disk) and disks specially prepared in Data Storage Institute (DSI disk). In this section, only the preparation of DSI disk is reported. The disk substrate material is aluminum-magnesium (Al-Mg) coated with nickel-phosphorus (NiP). The size of the disk is 95 mm in diameter. The overall disk preparation process is summarized in Fig. 3.9. In general, the disks prepared in DSI undergo the following processes:

- a) The substrates are first sputtered with an intermediate layer of carbon overcoat. It is then lubricated using dip-coating technique with a luber (DSI 2000 Mini-luber) and lube-buffed by a modified EDC 1800A disk buffing system.
- b) A disk after lubing has two layers, i.e., the bonded lube and free lube layer. For preparation of disks with bonded lube only, the disks are rinsed with a solvent to remove the top free lubricant layer.
- c) The lube and carbon uniformity of the buffed disks were observed by the Optical Surface Analyzer (OSA) know as Candela 5100.
- d) A disk Burnish/Glide/Certifier system (MG4000) was used for the glide test. The topographies and roughness of disks were measured and analyzed by Atomic Force Microscopy (AFM).

More details of the disks preparation process will be covered in the next section.

Fig. 3.9. Summary of the overall disk preparation process in DSI.

3.4.1 Layer structure of disk

Disk average surface roughness plays an important role in the surface force interaction; hence, it is desirable to use disks with very small surface roughness value, i.e., “super-smooth” disk. These “super-smooth” disks will then allow the slider to fly at close proximity (a few nanometers) to the disk surface. Deposition of a magnetic recording layer will increase the disk surface roughness. Therefore, using DSI disks is to minimize the surface roughness value as such disks are prepared without any magnetic recording layer. The typical parameter used for surface roughness characterization is the average surface roughness (R_a) which is defined as the arithmetic mean of the deviations of the roughness profile from a mean line.

The different film layer structures of the disks are schematically illustrated in Fig. 3.10. In order to compare disks with different roughness levels, structure A disks can also be prepared by having magnetic recording layer. This will increase the overall roughness of the disk surface fabricated from the same batch of disk substrate.

(a) Structure A

(b) Structure B

(c) Structure C: Structure A + Recording Layer

Fig. 3.10. (a) Disk film layer structure A; (b) structure B; (c) structure C: structure A with recording layer.

3.4.2 Disk Lubing and Buffing

After the sputtering process, the disks are dip-coated with a layer of lubricant using a luber designed in DSI. The schematics explaining the lubing processes are illustrated in Fig. 3.11. The servo motor of the luber will provide the vertical up and down motion of the disk and control the speed of withdrawal of the disk from the container of lubricant. Initially, the disks are placed on the disk holder shaft. The servo motor will extend the disk holder shaft down until the disks are fully immersed in the lubricant. The disks are then kept immersed in the lubricant about 15~20 min to allow sufficient time for the lubricant to be fully bonded to the disks surfaces. The disks are subsequently withdrawn from the lubricant at a constant speed of about 50 mm/min. This is to ensure uniform lubricant thickness for the disks lubed. The different lubricants used, such as Z-DOL, Z-Tetraol, A20H, ADOH, DDOH and DDPA are diluted with Vertrel XF solvent at a concentration level of 0.1 % wt.

After dip-coating the disk with a layer of lubricant, the surface of the disk is observed with an Optical Surface Analyzer (OSA) to capture the lubricant thickness uniformity image. A typical image is shown in Fig. 3.12. The “slanted lines” shown in this OSA image are caused by the low frequency floor vibration during the lubing process which resulted in the uneven lubricant thickness uniformity on the disk surface. The number of particles count on the disk surface is also scanned with the OSA as shown in Fig. 3.12. These particles seen on the disk surface could be due to the environmental contamination or they are particles from the lube container.

Fig. 3.11. (a) Disk mounted on holder shaft sitting above lubricant container. (b) Servo motor lowered the disk into the lubricant container. (c) After disk is fully immersed in lubricant, it is withdraw out from the container at a constant speed.

Fig. 3.12. Disk surface lube uniformity and particle count image before buffing.

In order to improve the lubricant thickness uniformity and reduce the particle count on the disk surface, the disk must be buffed. During the buffing process, a special tape will lightly contact the disk surface lubricant and move across the disk surface at a pre-determined velocity. Schematic of the buffing process is illustrated in Fig. 3.13. The tape moving velocity and the amount of contact force between the tape and disk will directly influence the lubricant uniformity and particle count on the disk surface. Too much contact force will cause over-buffing and expose the magnetic layer which causes corrosion to happen easily; too small contact force will not be able to effectively remove the particles on the disk surface. Therefore, care must be taken when selecting the correct contact force and moving tape velocity. After buffing, the disk is rescanned with the OSA for its lubricant thickness uniformity and particle count. As shown in Fig. 3.14, the “slanted lines” previously observed in Fig. 3.12 has disappeared after buffing. The particle count on the disk surface has also been reduced after buffing as shown in Fig. 3.14. Thus, better lubricant thickness uniformity and lower particle count are achieved after buffing process.

Fig. 3.13. Schematic of lube-buffing process.

Fig. 3.14. Disk surface lube uniformity and particle count image after buffing.

After the lubing process, the lubricant film will consist of two layers. One layer is chemically bonded onto the carbon surface (bonded lube) and the other layer is mobile (free lube). This free lube layer can be rinsed away using a solvent because it is not chemically bonded onto the substrate surface yet. Therefore, in order to have a bonded-lubed-only disk, some of the lubed disks are dipped into clean Vertrel XF solvent for several minutes to rinse away the mobile lubricant layer.

An experiment to determine the rinsing time to achieve bonded lubricant is also conducted. The disk is first submerged into Vertrel XF solvent to rinse away the free lubricant layer. Lubricant reflectivity (inversely related to lubricant thickness) of the disk surface is then measured using the OSA. The disk is then submerged back into the solvent to continue rinsing the rinsing process. The disk is taken out and checked for its lubricant reflectivity again. If the reflectivity value is the same as the previous scan, that means, only the bonded layer is left on the disk. If the reflectivity value is

different, that means, there is still some more free lubricant is left on the disk surface and it has to be submerged back into the solvent to remove the rest of the free layer left on the disk. This process is repeated until the reflectivity of the lubricant remains unchanged, i.e., only the bonded lubricant layer is left on the disk surface.

Figs. 3.15 and 3.16 show the lubricant reflectivity (inversely related to lubricant thickness) obtained from the OSA under different rinsing times. In Fig. 3.15, the Z-Tetraol lubricant reflectivity difference becomes negligible for the rinsing times of 10 min and 15 min. This suggests that what is left on the disk surface is only bonded Z-DOL lubricant. Fig. 3.16 shows that the Z-DOL lubricant reflectivity remains almost the same after rinsing time of 15 min. This suggests that Z-DOL lubricant requires a 10 to 15 min of rinsing interval to retain only bonded lubricant layer on the disk surface. Similar experiments are conducted for Moresco lubricants, i.e., A20H, ADOH, DDOH and DDPA to determine the rinsing time required to retain only the bonded lubricant layer on the disk surface.

Fig. 3.15. Z-Tetraol lubricant reflectivity/ thickness under different rinsing time

Fig. 3.16. Z-DOL lubricant reflectivity/thickness under different rinsing time.

3.4.3 Gliding height test

To study short range surface interaction forces effectively, the head-disk spacing needs to be very small. This requires a disk of a very low glide height. The targeted glide height for the disk prepared in DSI is 3.5 nm. Disk glide height is defined as the flying height at which asperities are detected with a slider equipped with a Piezoelectric Transducer (PZT) known as the glide head. This glide height is the slider-disk spacing at which contact between the slider and the highest asperities of the disk surface occurs. Fig. 3.17 schematically illustrated this. To determine if the disk has a glide height that is equal or less than 3.5 nm, a glide test needs to be conducted.

During the glide test, the glide head flies over a disk medium at a predetermined clearance which is the glide height. The schematic of a PZT glide head is illustrated in Fig. 3.18. If contact occurs between the glide head and disk asperities, the contact

will excite the slider to vibrate. The intensity of contact vibration will be detected by the PZT and outputted as the Glide signal on the data acquisition system.

Fig. 3.17. Schematic illustrating the definition of disk Glide Height

Fig. 3.18. Schematic of a typical PZT Glide head.

1) *Glide head calibration*

The targeted glide height is 3.5 nm. This requires flying the glide head above the disk surface at this glide height. Thus, calibration on the glide head is required. A commercially available bump disk is used for the glide head calibration. The bump disk is of laser generated bumps with bump height of 3.5 nm, bump spacing of $0.41\ \mu\text{m} \times 0.41\ \mu\text{m}$, as measured by the atomic force microscope (AFM). The bump region on the disks surface starts from radius 30.4 mm to 30.6 mm. During calibration, the glide head will fly across the disk surface from the outer diameter (OD) to the inner diameter (ID) at a certain constant linear velocity (CLV), as schematically illustrated in Fig. 3.19. Maintaining the same disk linear velocity is important in order to maintain the same flying height when the slider flies from OD to ID. Initially, high CLV is used, thus there is no contact when the glide head seek across the bump region. The CLV is then reduced until contact between the glide head and asperities occur. In this test, the CLV recorded when contact between the glide head and the bump region occurs is about 10.16 m/s. Therefore, by flying the glide head at 10.16 m/s will ensures a glide height of 3.5 nm.

The glide head calibration result, when the glide head contacts the 3.5 nm bump, is shown in Fig. 3.20. Calibration is conducted before, during and after the glide test. Slight glide signal (0.10 V to 0.40 V) is always detected during all the tests. This showed that the calibrated glide height of the glide head is maintained at about 3.5 nm during the entire glide test.

Fig. 3.19. Schematic of a glide head seeking across a bump of 3.5 nm high.

Fig. 3.20. Glide head calibration result before, during and after glide test.

2) Glide height testing and results

The calibrated gliding head will be used for checking the gliding height of the disks that are to be used for the experimental study. The disk samples to be tested will be mounted on the glide tester. The glide head will fly across the disk surface from the outer diameter of 40.64 mm to the inner diameter of 30.48 mm. The disk will be rotated at its calibrated constant linear velocity (CLV) of the gliding head (in this case,

it is 10.16 m/s as mentioned in the earlier section). In the event when the surface asperities are greater than 3.5 nm, contact between the asperities and glide head will occur. This causes vibration on the glide head and the PZT will generate a glide signal, indicating that the asperity height is 3.5 nm or above. As a result, the disk samples will have failed the 3.5 nm glide test. On the contrary, if only very slight glide signal (<0.40 V) is detected at the gliding testing velocity, the disk samples will be classified as having passed the 3.5 nm glide test and can be used for the experiment.

Three main types of disk samples are tested. Disk sample A is of structure A; disk sample B is of structure B and disk sample C is of structure C. (refer to Fig. 3.10 for their respective disk structure). Within each disk samples, different lubricants such as Z-DOL, Z-Tetraol, DDOH, DDPA, A20H and ADOH, are used. Disk with bonded lube only and disks with both bonded and free lube are also prepared with these lubricants. Disks that passed the 3.5 nm glide test will be qualified to be used for the experiment. An example of the glide test result is shown in Fig. 3.21. This glide test result comprises of sample B disk of the following type of lubricant used, three Z-Tetraol lubed disks (1 free lube and 2 bonded lube); three DDPA lubed disks (all bonded lube); three DDOH lubed disks (all bonded lube); three ADOH lubed disks (all bonded lube); three A20H lubed disks (all bonded lube). Out of these fifteen disks, only three disks failed the glide test. The three disks all are classified as failed because the glide signal detected is greater than 0.40 V (refer to Fig. 3.21). These disks could be still used for experiment because their inner diameter (ID) and middle diameter (MD) passed the glide test of 3.5 nm glide height. However, experiments can only be conducted on the inner and middle diameter of these disks where the glide signals are less than 0.40 V.

Fig. 3.21. Disk Sample B glide signal for the different types of lubricant after 3.5 nm glide test. Out of the 15 tested disks, only 3 disks failed the glide test. They are DDPA, DDOH and Z-Tetraol bonded lube disk.

3.4.4 Disk surface roughness

The disk average surface roughness (Ra) is measured with Atomic Force Microscopy (AFM). Typical results for the three different types of disk structures are shown in Fig. 3.22. Disk of structure B has the lowest Ra of only 0.13 nm; disk of structure A has a slightly higher Ra of 0.18 nm due to its additional layer of Tantalum (Ta); and disk with recording layer (structure C) has the highest Ra as measured to be 0.21 nm.

(a)

(b)

Fig. 3.22. (a) AFM measurement results of average surface roughness (Ra) for structure A disk, (b) structure B disk and (c) structure C disk.

3.5 Preparation of Slider and HGA

Two types of slider design are prepared for this experimental study. One type has a good linear relationship between its flying height and rotational velocity of the disk. Another type is designed to have air bearing low stiffness on its trailing pads so as to increase its sensitivity to surface interaction forces.

3.5.1 Type 1 Slider

1) Air bearing surface (ABS) design

Type 1 Slider is a kind of commercial slider designed by IBM. Its ABS layout is shown in Fig. 3.23. This slider has the following physical parameters: a dimension of 1.25 mm by 1.0 mm by 0.30 mm, a designed gram load of 2.50 gram, a crown of 6 nm, a camber of 1.5 nm, a shallow step depth of 0.12 μm , and a cavity depth of 1 μm . The slider physical definitions of these parameters are schematically illustrated in Fig. 3.24.

Type 1 Slider has a large trailing pad which makes it suitable for the harmonic vibration analysis. This is because a large surface area effectively increases the electrostatic force between the slider and disk surface as seen in equation (3.1). This allows the slider to be more sensitive to harmonic vibration when an ac voltage is applied across the slider and disk interface. Using the head-disk interface simulation program (developed by University of California, Berkeley), the air bearing pressure distribution across the slider is obtained and plotted as seen in Fig. 3.25.

Fig. 3.23. ABS layout of Type 1 slider designed by IBM

Fig. 3.24. Physical definition of slider's parameter

Fig. 3.25. Air pressure plot of Type 1 Slider (radius = 27 mm; skew angle = 0°).

2) *Flying height profile*

The Head Gimbal Assembly (HGA) as shown in Fig. 1.9 is assembled with the Type 1 Sliders. After assembly, these HGAs are mounted onto a commercial dynamic flying height tester designed and built by KLA-Tencor to test for the slider flying height profile. The flying height testing result is shown in Fig. 3.26. The testing radius is set at the inner disk diameter of 27.0 mm because disk surface characteristics such as lubricant and surface roughness are more uniform at the inner diameter than the outer diameter. This will give a more consistent flying height profile for the slider. The skew angle of the disks is all set at 0° to avoid any potential skew angle effect. This is because different skew angles will cause different flying characteristics. The testing point is located at the center trailing edge as illustrated in Fig 3.23, off the read/write sensor. The measured flying height of this slider is linear with the disk rotational speed as shown in Fig. 3.26.

In order to increase the electro-spacing of head disk interface in the experiment, a thicker layer of Diamond Like Carbon (DLC) is deposited on the surface of the Type 1 Slider. The electro-spacing definition of the Type 1 Slider and the modified Type 1 Slider (with 20 nm thick DLC) are schematically illustrated in Fig. 3.27. Electro-spacing is the distance between two electrically conductive layers, in this case, it is the slider's TiC base material and the disk surface beneath the carbon overcoat (as both lubricant and diamond like carbon (DLC) overcoat are not good electrical conductor). The DLC is electrically non-conductive, thus by increasing its thickness will result in increasing the electro-spacing.

Fig. 3.26. Flying height profile of Type 1 Slider measured using dynamic flying height tester (radius = 27 mm; skew angle = 0°).

Fig. 3.27. Electro-spacing definition of Type 1 Slider and modified Type 1 Slider with different DLC layer thickness.

3) Modeling and analysis of surface interaction forces on type 1 slider.

Simulation is done with ABS simulation software (CMLAir32 V6.56) developed by researchers in the Computer Mechanics Laboratory (CML), University of California Berkeley. This software is a kind of industry standard tool for ABS design and evaluation. The flying height measuring location is at ($x=1.24$ mm, $y=0.5$ mm) of the slider air bearing surface (refer to Fig. 3.23). This is where the gap flying height point lies.

The electrostatic force effect is simulated by applying an electrical potential difference across the head-disk interface. Fig. 3.28 clearly shows the attractive nature of the electrostatic force. By increasing the electrostatic potential, the flying height is reduced due to the increased attractive electro-force. According to the equation (3.1),

the attractive electrostatic force (F_{el}) becomes much stronger with the increase in electrical potential (V) since F_{el} is proportional to V^2 . This can be observed in Fig. 3.28 where the slope becomes steeper with increasing electrical potential, i.e., the flying height becoming lower. The stiffness of the trailing pad is also measured by the ABS simulation software. The result, as shown in Fig. 3.29, indicates an increase in stiffness on the trailing pad as the electrical potential is increased across the interface. The change in stiffness is observed to be more prominent at higher electrostatic potential, i.e., the slope in Fig 3.29 becomes steeper with an increase in electrical potential. An increase in electrical potential across the head-disk interface correspondingly increases the electrostatic force between them. This increases the stiffness of the air bearing. In addition, the reduction in head-disk spacing due to the increase in electrostatic force between the head and disk also contributes to the increase in air bearing stiffness. This is because, the air flowing through a smaller head disk spacing is further compressed, resulting in increased air bearing stiffness.

Fig. 3.28. Effect of electrostatic force on flying height.

Fig. 3.29. Effect of electrostatic force on stiffness.

The effect of the intermolecular force is also simulated. The model that is used to simulate the intermolecular considered only van der Waals force because it is the dominant surface interaction force at very low flying height of 0.4~5 nm [51]. The formula for the intermolecular force is as follows [51],

$$F_V = \frac{A}{6\pi} \iint_{\Delta} \frac{dxdy}{h(x,y)^3} - \frac{B}{45\pi} \iint_{\Delta} \frac{dxdy}{h(x,y)^9} \quad (3.11)$$

where A is the Hamaker constant, with a typical value of about $10^{-19} J$. The typical value for constant B can be $10^{-76} Jm^6$. x and y are the relative positions on the slider surface. The first term on the right hand side of equation (3.11) is the attractive van der Waals force, and the second term is the repulsive intermolecular force. The attractive and repulsive portions of the force have different acting ranges. The attractive van der Waals has a longer acting range than the repulsive portion. When spacing between the surfaces of the slider and the disk is less than 10 nm, these two surfaces will first experience an attraction force. The strength of the attraction force will increase as the spacing between the two surfaces reduces until a point when the

spacing is small enough to make the short range repulsive force active. The range at which repulsive force becomes active is estimated to be about 0.32 nm. Therefore, from the equation (3.11), the attraction strength of the intermolecular force is seen to be very much dependent on the Hamaker constant, A .

The effect of the intermolecular force on the flying characteristics of the slider is investigated by varying the Hamaker constant value A in the head-disk interface simulation process. Based on the analytical simulation conducted, the simulation results are shown in Figs. 3.30 and 3.31. It is observed that increasing intermolecular force (due to the increase in Hamaker constant A) resulted in the reduction of the slider flying height and air bearing stiffness. However, there is only a slight decrease in air bearing stiffness with an increase in the intermolecular force. After comparing the results of electrostatic force and intermolecular force effect, the electrostatic potential is found to cause more prominent changes to the flying height and stiffness than intermolecular force.

Fig. 3.30. Effect of intermolecular force on flying height.

Fig. 3.31. Effect of intermolecular force on trailing pad air bearing stiffness.

3.5.2 Type 2 Slider

1) Air bearing surface (ABS) design

A different type of slider is specially designed to study the effect of surface interaction forces. The slider ABS layout is schematically shown in Fig. 3.32. This type of slider is designed to enhance the sensitivity of the slider's dynamic performance to the effect of the short range surface forces acting around the trailing pad. This slider has a trailing pad that is wide in the width direction of the slider and narrow along the length direction of the slider. By designing the slider in this manner, the air bearing force under the trailing pad can be greatly reduced due to the slider's shorter length direction and at the same time the surface interaction forces at the slider's trailing pad can be stronger as the trailing pad is wider in this case.

Fig. 3.32. Type 2 slider ABS layout.

Fig. 3.33. Air Pressure distribution profile of type 2 slider.

The slider's dimension is 1.235 mm by 1.0 mm by 0.30 mm, gram load is 1.0 gram, crown is 20 nm, camber is 3 nm, shallow step depth is 0.1 μm , and cavity depth is 1.5 μm . Its air pressure distribution is shown in Fig. 3.33 using the ABS simulation program.

2) Contamination problem of Type 2 Slider

The low stiffness Type 2 Slider has been fabricated and its 3 Dimensional view of its air bearing surface is shown in Fig. 3.34. This slider is assembled to form Head Gimbal Assembly (HGA) level and subsequently tested for its flyability. During the flyability test, the trailing pad is found to be contaminated easily. The possible reasons for the contamination can be: (a) The wide trailing pad allows particles to be

collected easily. (b) The deep etching depth in front of the trailing pad makes it easy for the particles to pass through it and accumulate on the pad. Due to such serious contamination concerns which lead to a flyability problem, this slider cannot be used for testing unless it is further modified. Thus, only the Type 1 Slider will be used for all experimental testing for the rest of this research work.

Fig. 3.34. 3D image of a fabricated Type 2 Slider

3.6 Summary

Harmonic vibration method is proposed in this chapter to determine the short range surface interaction forces. This method can give a good indication on the intensity of the surface interaction. Modeling of electrostatic force across a slider-disk interface is also presented in this chapter. Previous modeling of the electrostatic force in many other journal papers mainly uses two parallel plates to simulate the slider-disk interface. The author improves this modeling by considering a horizontal plate and an inclined plate to better simulate the actual slider-disk interface condition. This is because, the slider is actually flying above disk at an inclined degree known as pitch angle. Modeling of slider vibration under an externally applied voltage is also done and it is found that the intensity of surface interaction force is related to the stiffness and damping at the slider-disk interface. The experimental platform mainly consisting of the head-disk testing stand, laser Doppler Vibrometer (LDV) system, acoustic emission (AE) sensing system and external voltage supplier system is setup to study the effect of surface interaction forces. Finally, the overall disk and slider preparation processes are presented in the latter part of this chapter.

CHAPTER 4

Experimental results of surface interaction forces study

4.0 Introduction

An experimental study of the surface interaction forces based on the second harmonic vibration method mentioned in chapter 3 is carried out. This method has been applied to determine the influence of various parameters such as the rotation speed, lubricant thickness, slider-disk contact and lubricant structure on the contact potential measurement at the slider-disk interface. A characteristics study of the second harmonic vibration at the slider-disk interface under various influences such as air bearing stiffness, lube-induced meniscus and different electro-spacing is also carried out in this chapter. Lastly, there will be an attempt to do a relative ranking of the surface interaction forces based on a specially designed experiment.

4.1 Harmonic vibration methodology and sample preparation

4.1.1 Basic of Harmonic Vibration methodology

The fundamentals of the harmonic vibration method have been mentioned in chapter 3.2. This method involves applying an ac and dc voltage source across the slider-disk interface. If a sufficient voltage source is applied across the slider and disk, the slider will be attracted to the disk surface due to the electrostatic force effect. The

experimental platform to measure the harmonic vibration has already been established in previous chapter as illustrated in Fig. 3.5.

The applied voltage source consists of an ac and dc component. The ac voltage source of a fixed amplitude (A) and fundamental frequency (ω) will cause the slider to vibrate at the first and second harmonics, i.e., ω and 2ω respectively. A Laser Doppler Vibrometer (LDV) system as shown in Fig. 3.5 is used to measure these vibrations and subsequently the computer will display its frequency spectrum after data acquisition and processing. A typical frequency spectrum is shown in Fig. 4.1 where the input ac voltage frequency is set at 30 kHz and amplitude at 1.0 V. Notice that there are two obvious peaks in Fig. 4.1, i.e., 30 kHz and 60 kHz. These frequencies corresponded to the first and second harmonic vibration respectively. The first harmonic vibration has an amplitude of 0.76 mV and second harmonic vibration has an amplitude of 0.65 mV. For comparison purposes, the following parameter will be kept the same for all experiments unless otherwise stated. These parameters include the disk testing radius, the slider skew angle, and the fundamental ac excitation frequency.

Fig. 4.1. Frequency spectrum displaying first and second harmonic vibration.

4.1.2 Sample preparation

Table 4.1 summarizes all the different types of sliders and disks that will be used in the experiments. These experiments include using two types of sliders and four types of disk with different structures. Table 4.2 shows the different types of lubricants and their respective properties used in the experimental studies. Using different types of sliders, disks and lubricants will create different levels of surface interaction force. This will allow testing of different surface interaction forces at the slider-disk interface.

Table 4.1

Definition for different types of slider and disk used in experiments.

Type of Slider / Disk	Characteristics
Slider A	Type 1 slider
Slider B	Modified Type 1 Slider (with 20 nm DLC coating)
Disk A	Structure A (DLC+Ta+substrate)
Disk B	Structure B (DLC+substrate)
Disk C	Structure A + Recording layer
Disk D	Commercial Disk from SDK

Table 4.2

Various types of disk lubricants and its properties

No.	Lubricant	End Group Type	OH end group	Manufacturer
1	Z-DOL	Double	Yes	Solvay Solexis
2	Z-Tetraol	Double	Yes	Solvay Solexis
3	A20H	Double	Yes	Moreseco
4	ADOH	Double	Yes	Moreseco
5	DDOH	Single	Yes	Moreseco
6	DDPA	Single	No	Moreseco

4.1.3. Using harmonic vibration method for contact potential measurement

A change in the applied dc voltage, V_{dc} will cause the amplitude of the first harmonic vibration of the slider to be changed. The first harmonic vibration amplitude of the slider will reach a minimum value at a certain applied dc voltage. According to equations (3.6) and (3.7), this minimum value will be the point where contact potential (V_{con}) value lies, since $V_{dc} = -V_{con}$. Fig. 4.2 shows the relationship between dc voltage, V_{dc} and first harmonic vibration amplitude. Disk A, with the bonded Z-DOL lubricant and slider B, is used in this measurement. The range of applied V_{dc} is normally adjusted from -1.20 V to +1.20 V. From Fig. 4.2, it is observed that with the increase in V_{dc} , the first harmonic vibration amplitude decreases initially till it reaches a minimum point where the first harmonic vibration amplitude starts to increase. The voltage at the minimum point corresponds to the contact potential value of the head-disk interface.

To determine the minimum point accurately, the points of decreasing amplitude and increasing amplitude are separated and curve fitted with linear trend lines. The equation of these trend lines will be determined and their intersection will be where the contact potential point lies. Fig. 4.3 illustrates the two trend lines and their respective equations. The equations of the two trend lines in Fig. 4.3 are:

$$y = a_1 V_{dc} + a_2 = 5.6867 V_{dc} - 1.1993 \quad (4.1)$$

$$y = b_1 V_{dc} + b_2 = -5.70 V_{dc} + 1.1573 \quad (4.2)$$

At the intersection point of the two lines:

$$\begin{aligned} V_{dc} &= (b_2 - a_2) / (a_1 - b_1) = (1.1573 + 1.1993) / (5.6867 + 5.7) \\ &= 0.21 \text{ V} \end{aligned} \quad (4.3)$$

Since $V_{dc} = -V_{con}$, the contact potential, V_{con} in this case is about -0.21 V.

Fig. 4.2 Relationship between first harmonic vibration amplitude and V_{dc} of bonded Z-DOL lubed disk

Fig. 4.3 Calculation of the contact potential value.

4.1.4 Primary characteristics of 2nd harmonic vibration on V_{ac}^2

The relationship of the second harmonic vibration amplitude and the square of ac voltage, V_{ac}^2 is tested by applying different ac voltage while measuring its corresponding second harmonic vibration amplitude. The rotational speed of the disk is set at 1000 rpm, Disk A lubed with Z-Tetraol and slider B is used. It is observed that the second harmonic vibration amplitude is linear with V_{ac}^2 as shown in Fig. 4.4. The slope of this line is dependent on the stiffness and damping ratio of the head-disk interface according to the previous analysis in chapter 3.2.2.

Fig. 4.4 Relationship of second harmonic vibration with V_{ac}^2

4.2 Characteristics studies of contact potential at the slider-disk interface

The contact potential value at the head-disk interface may influence the stability of the head-disk interface because it can create a certain level of attractive electrostatic force between the slider-disk interface which reduces the slider flying height [29]. Therefore, it is important to understand how the contact potential value across the slider-disk interface may vary due to different testing parameters such as, disk

rotational speed, slider flying duration, lubricant thickness and structure. This section studies influences of slider-disk parameters on the contact potential value.

4.2.1 Influence of different rotational speed on contact potential

Disk A (lubed with Z-Tetraol) and slider A are used in this experiment. The rotational speed of the disk is reduced from 10 000 rpm to 1000 rpm at a discrete step of 1000~2000 rpm. At each discrete step, their respectively contact potential value is measured and plotted out in Fig. 4.5. Generally, the contact potential averages around -0.25 V when rotational speed is not too low (>1000 rpm). However, when the rotational speed reduces to 1000 rpm, there is an increase in the contact potential value to about -0.38 V. The reason is that, at low rotational speed, the slider's air bearing may not be able to provide sufficient upward lift. Therefore, some intermittent contact between the slider and slider's surface may have occurred. This will result in tribo-charge built up between the slider-disk interface due to friction contact between slider and disk surfaces. This will have caused the increase in the contact potential value at the slider-disk interface.

Fig. 4.5. Relationship of contact potential with various rotational speed.

4.2.2 Influence of different lubricant thickness on contact potential

In this experiment, how lubricant thickness will influence the contact potential at the slider-disk interface is determined. Three different thickness of Z-DOL are lubed onto Disk A. The detailed preparation process is described in chapter 3.4. The three different lubricant thicknesses in ascending order are: i) without lubricant (only DLC layer); ii) with bonded lubricant only; and iii) with both bonded lube and free lube. The rotational speed is set at 2000 rpm. Contact potential with various lubricant thickness is determined and shown in Fig. 4.6. The contact potential for the disk without lubricant is -0.02 V, for the disk with bonded lube is 0.21 V, and for disk with bonded and free lube is 0.43 V. Through this experiment, it is found that thicker lubricant increases the contact potential value.

Fig. 4.6. Contact potential with different lubricant thickness

4.2.3 Influence of slider's flying duration on contact potential

The relationship of contact potential with the slider flying time is determined in this experiment. Type A disk lubed with Z-Tetraol lubricant and type B slider is used in this experiment. Fig. 4.7 shows the relationship of contact potential with the length of the slider flying duration. At every 40 min interval, contact potential value is measured. The total test duration is 120 min. After the slider has flown continuously over the disk for 120 min, the contact potential is found to have changed from -0.60 V to -0.34 V. Generally, it is observed that the absolute contact potential value will gradually decrease with flying duration. From Fig. 4.7, it can be observed that there will be a minimum value that contact potential will stabilize as the flying duration is prolonged.

Fig. 4.7. Relationship of contact potential value with slider flying duration.

4.2.4 Influence of slider-disk contact on contact potential

When the slider is flying at a very low flying height of less than 5 nm, slight contact between the slider and disk surface may occur. The disk surface has a certain level of roughness and asperity height. The disk used in this test has a roughness of about 0.25 nm and measured asperities height of about 3.5 nm. On top of the disk surface, there

is a layer of lubricant that is about 2 nm thick. Thus, when the slider is flying at 5 nm or less, it will cause some slight contact between the slider surface and the top lubricant layer, as well as some high surface asperities on the disk surface. If the slider is allowed to fly even lower, stronger contact will occur between the slider and disk asperities' surface. This will cause the slider to fly unstably and might even scratch the disk surface and cause read-write failure. In the event of contact, tribo-charge can build up too at the slider-disk interface. This is important to the stability of the slider-disk interface as it contributes to additional electrostatic attraction force at the slider and disk interface. Thus, this experiment will attempt to study whether the additional tribo-charge generation during contact may influence the value of contact potential that is present at the slider-disk interface.

In this test, in order for slider-disk contact to occur, the slider-disk spacing has to be reduced. This can be done by reducing the rotational speed of the disk gradually till contact between slider and disk has occurred. Contact is detected by a highly sensitive AE sensor as mentioned in chapter 3.3.1. Subsequently, the rotational speed is increased till contact cease. Slider A and Disk D are used in this measurement. V_{ac} is kept at 0.50 V and V_{dc} at 1 V. From the result shown in Fig. 4.8, increasing magnitude of the first harmonic vibration was observed after slider-disk contact has occurred. The first harmonic vibration magnitude did not reach a stable value even after 10 min of flying. Since first harmonic vibration is related to contact potential, the contact potential is shown to be unstable after slider-disk contact.

Fig. 4.8. Increasing first harmonic vibration after strong slider-disk contact.

By increasing the disk rotational speed to 1000 rpm and adjusting the V_{dc} accordingly, the contact potential value is measured 10 min after contact occurred. The result is plotted out in Fig. 4.9. Before any contact, low contact potential of only -0.09 V is measured. However, after contact, contact potential value increases to -0.23 V. Therefore, this result shows that slider-disk contact will cause changes (unstable) to the first harmonic vibration and increase the contact potential value at the same time.

Fig. 4.9. Contact potential before & 10 min after strong contact.

It is also important to observe the phenomena at light head-disk contact. The difficulty is how to achieve very light contact. A method that can effectively control the spacing between the slider and disk has to be identified. What was used in this thesis involved applying a strong enough current to the write head to cause a few nanometer of thermal head protrusion out of the slider air bearing surface. If the slider is flying just a few nanometers above the disk, very light contact will be achieved. By applying this principle, a small amount of dc voltage is applied to the write head. This small amount of dc voltage is increased gradually till slight contact is observed by a Laser Doppler Vibrometer (LDV). LDV is used here instead of AE sensor because it is more sensitive to light head-disk contact. Fig. 4.10 shows light contact has occurred when applied dc writing voltage is increased to 0.8 V. The resistance of the writing element is about 9.7Ω , which makes the writing current to be about 82 mA. Immediately after very light contact has occurred, the dc voltage is removed to prevent any further contact. The result of the measured contact potential before and after very light contact is plotted out in Fig. 4.11. The rotational speed is set to a low value of only 1000 rpm. Disk D and slider B are used in this test. Before contact, the measured contact potential value is -0.42 V. After very light contact, the contact potential value becomes -0.33 V. Therefore, any very light contact will reduce the amplitude of contact potential but the amount of contact potential change is not very significant.

Fig. 4.10. Light contact caused by head thermal protrusion.

Fig. 4.11. Contact potential before and after slight contact.

4.2.4 Influence of different lubricants with different functional end group

Presently, most research papers apply slider touch down and take off methodology to study the effect of different lubricant structures on the slider-disk interaction. This method involve reducing the slider flying height through reducing the disk rotational speed till the slider contacts the disk surface (touch down). The slider flying height is then increased by raising the rotational speed till the slider is separated from the disk surface (take off). The difference between the slider touch down velocity and take off velocity, known as flying height hysteresis, is measured and usually used as an indicator of meniscus force effect caused by lubricant. The amount of the flying height hysteresis will relate to the intensity of slider-disk interaction, i.e. larger flying height hysteresis will mean stronger lubed-induced interaction between the slider and disk. However, this method causes contamination problem because debris and particles can be generated when the slider contacts the disk surface. Therefore, a non-contact method is preferred to avoid such problems.

This experiment applies a non-contact method to study the influences of different lubricant structure on the contact potential that is present at the slider-disk interface. It involves applying the 2nd harmonic vibration testing principle, as stated in chapter 3.2. Two main types of lubricant structure are studied in this chapter, i.e. lubricant with doubled-ended functional end groups and lubricant with single-ended functional end group lubricant structures. The functional end group of the lubricant is an important characteristic determining the bonding strength of the lubricant's main chain to the disk surfaces. Thus, it will be important to study how the different functional end group will affects the contact potential value at the slider-disk interface. Four different types of lubricant are selected in this experiment. They are the double ended

functional end group lubricant, Z-DOL and Z-Tetraol; and the single ended functional end group DDOH and DDPA. Their respective lubricant structures are illustrated in Fig. 4.12.

Double-ended functional end group lubricant:

(a) Z-DOL

(b) Z-Tetraol

Single-ended functional end group lubricant:

(c) DDOH

(d) DDPA

Fig. 4.12. Lubricant structure of double-ended and single-ended lubricants.

In order to achieve a fair comparison among the 4 types of lubricants, only the bonded lubricants are used for testing. This will eliminate the differences due to different mobile lubricant thickness. In the experiment, the rotational speed is kept at 2000 rpm; and type A disk and type B slider are used for the entire experiment. The dc voltage is also change from -1.0 V to +1.0 V to determine the contact potential value. A total of twenty contact potential measurements are made for the different lubricants and the results are shown in Fig. 4.13. The average and standard deviation of the measured contact potential value of the various lubricants are summarized in Table 4.3.

Fig. 4.13. Contact potential value of the various lubricants.

Table 4.3.

Contact potential of disks with double ended and single ended lubricant end group

Lubricant Type	Type of End Group	Average contact potential value	Standard Deviation of contact potential value
Z-DOL	Double	-0.25 V	13 mV
Z-Tetraol	Double	-0.24 V	15 mV
DDOH	Single	-0.18 V	38 mV
DDPA	Single	-0.12 V	40 mV

From the results observed in Fig. 4.13 and table 4.3, the contact potential values of double-ended lubricants (Z-DOL and Z-Tetraol) are generally lower than single-ended lubricant (DDOH and DDPA). Double-ended lubricants have shown stable contact potential measurement with only a small standard deviation of 13~15 mV. However, single-end lubricant, as shown in Fig. 4.13, exhibited unstable contact potential measurement with a much larger standard deviation of 38~40 mV. This is because single-ended lubricant has one end of its main chain free, not bonded to any surfaces, while the other end is either bonded to the slider surface or disk surface. Having one end of the lubricant main chain free would mean that the lubricant has a longer portion of its main chain length that is free. A longer free main chain length can lead to stronger slider-disk interaction which will cause unstable fluctuation of the slider [52]. This unstable fluctuation of the slider will lead to an unstable contact potential measurement.

However, for the double ended lubricant such as Z-DOL and Z-Tetraol, their length of the free main chain portion is effectively reduced by their double-ended functional end group. Double ended lubricant has both ends of its lubricant main chain bonded strongly to the slider and disk surface. This reduces the free portion of the lubricant main chain. Since the main free chain length is reduced, the intensity of slider-disk interaction will be effectively reduced. This will allow double-ended lubricant to have stable contact potential measurement than single-ended lubricant.

4.2 Characteristics studies of 2nd Harmonic Vibration at slider-disk interface

As mentioned in chapter 3, the electrostatic force will attract the slider towards the disk surface when there an ac and dc voltage source is applied across the slider-disk interface. The slider will vibrate if an ac voltage is applied. The vibration will have both the source fundamental frequency ω and its 2nd harmonic frequency 2ω . In the previous experimental result shown in Fig. 4.4, the 2nd harmonic vibration amplitude is linear with V_{ac}^2 . Based on the analysis in 3.2.2, the slope of the line in Fig 4.4 is dependent on the stiffness of the head-disk interface. The stiffness value will reflect the level of surface interaction force present at the head-disk interface. Thus, the amplitude of 2nd harmonic vibration is related to the intensity of surface interaction force.

Since the 2nd harmonic vibration is related to the intensity of the surface interaction force, it will be important to determine how different parameters such as rotational speed, air-bearing stiffness, electro-spacing and lubricant-induced meniscus will affect the 2nd harmonic vibration and thus the interaction forces between the slider and disk surfaces. The following section will describe the experiment to determine the influences of these parameters on the 2nd harmonic vibration.

4.2.1 Influences of air bearing stiffness on 2nd harmonic vibration.

To test the influences of air bearing stiffness on the 2nd harmonic vibration, different flying height is required and, therefore different rotational speeds of the disk have to be used. Also, to minimize the lubricant meniscus effect, only bonded lube disk is used in this test. Disk D with only boned lube layer and slider A are selected to be

used in this experiment. The testing radius on the disk is kept constant at 38.10 mm. The experimental platform used is previously shown in Fig. 3.5.

A simulation study to determine the flying height profile of this slider is conducted based on the experimental condition set in this test. No electrostatic force or intermolecular force model is applied in this simulation. This will allow only the air bearing stiffness to affect the slider flying height profile. The flying height profile and the positive upward force of the slider versus the different rotational speed are shown in Fig. 4.14a and Fig. 4.14b respectively. It is observed that both the flying height and positive upward force on the slider increase as the rotational speed increases. These are caused by the increased in air bearing stiffness as the rotational speed is increased.

(a)

(b)

Fig. 4.14. (a) Simulation result of slider flying height profile, (b) Slider positive upward force. Testing is done at radius 38.1 mm and 0° skew angle.

Fig. 4.15. Second harmonic vibration amplitude with bonded lube disk.

During the experiment, the 2nd harmonic vibration amplitude under different rotational speeds is measured and the results are shown in Fig. 4.15. It is observed that when the disk rotational speed increases from 1300 rpm to 3000 rpm, the amplitude of the 2nd harmonic vibration reduces. This can be explained from equation (3.11).

When the rotational speed is increased, the slider air bearing stiffness becomes larger. A larger air bearing stiffness will result in a smaller slider vertical displacement. This will cause a reduction in the slider 2nd harmonic vibration amplitude.

4.2.2 Influence of lube-induced meniscus on 2nd harmonic vibration amplitude

Lube-induced meniscus between the slider and disk is usually caused by the free lubricant layer on the disk surface. This is because the free lubricant layer is not chemically bonded to the disk surface. Therefore, such lubricant can be transferred to the slider surface. To test out the effect of the lube-induced meniscus on the 2nd harmonic vibration amplitude, similar experiment conditions and procedures are used as in 4.2.1, expect that free lube disk is used instead of bonded-lube-only disk. The experiment result of the slider 2nd harmonic vibration with free lube disk is shown in Fig. 4.16.

As rotational speed is increased from 1300 rpm to 3000 rpm, a trend similar to the one in chapter 4.2.1 is observed, i.e., the 2nd harmonic vibration amplitude reduces as the rotational speed increases. However, there is a significant difference in their 2nd harmonic vibration amplitude. By comparing Fig. 4.15 and 4.16, the disk with free lube layer has smaller 2nd harmonic vibration amplitude than the bonded lube disk. This is due to the increase in damping provided by the free lube layer on the disk surface which could have reduced the vibration of the slider.

Fig. 4.16. Second harmonic vibration amplitude with free lube disk.

A special phenomenon also occurs when rotational speed is at 1800 rpm, 2000 rpm and 2500 rpm. When rotational speed is increased to 2000 rpm from 1800 rpm, the harmonic vibration amplitude remained unchanged instead of becoming smaller, as shown in Fig. 4.16. And when the rotational speed is increased to 2500 rpm, there is a sudden increased in the 2nd harmonic vibration amplitude. This is a very different observation from the test in chapter 4.2.1. Initially, when the rotational speed started to increase from 1300 rpm, the slider flying height is very low (near asperities contact level). Because of low slider-disk spacing, menisci bridges may have formed between the slider and disk surfaces. This will provide damping and reduces the 2nd harmonic vibration amplitude. When the rotational speed is increased to 1800 rpm and 2000 rpm, the upward air bearing force becomes stronger and starts to break the menisci bridges between the slider and disk surface. When the rotational speed increased further to 2500 rpm, the upward air bearing force becomes even stronger and breaks the menisci bridges between the two surfaces. This will cause the slider to increase its 2nd harmonic vibration amplitude due to reduction in the damping effect of the free

lubricant. When rotational speed is further increased to 3000 rpm, the air bearing becomes stiffer and thus resulting in overall lowering of 2nd harmonic vibration amplitude.

4.2.3 Influences of electro-spacing on 2nd harmonic vibration

Electro-spacing is defined as the spacing between two conducting layers. In a typical slider-disk interface, the two conducting layers are the slider base material, TiC and disk magnetic layer as shown in Fig. 3.27. In order to study the electro-spacing effect on the 2nd harmonic vibration amplitude, different electro-spacing between the slider and disk is required. This can be done by preparing the disks with different lubricant thickness, i.e., a free lube disk, a bonded lube disk and a no lube disk. The different electro-spacing between the slider and disk is schematically illustrated in Fig. 4.17.

Fig. 4.17. Electro-spacing of different lubricant thickness.

Fig. 4.18. Second harmonic vibration amplitude of different lubricant thickness.

In this test, Disk B and slider B is used. The rotational speed of the disk is kept at 800 rpm and the testing radius and skew angle are set at 38.10 mm and 0° respectively. The testing results are shown in Fig. 4.18. The vibration amplitude of disk without lubricant is the highest and it is lowest for the disk with free lubricant. This is due to their difference in electro-spacing, i.e. the disk without lube has smaller electro-spacing than the free lube disk and thus it has larger electrostatic interaction. Although electro-spacing between the slider and disk is a good indication of the strength of the electrostatic interaction between them, it will be more accurate if the effective electro-spacing to indicate the strength of electrostatic interaction is determined. Effective electro-spacing is dependent on the material thickness and its dielectric constant, as defined by the following equation:

$$Material_Effective_Electro-spacing = \frac{Material_layer_thickness}{Material_dielectric_constant} \quad (4.1)$$

Effective electro-spacing can be derived from a two plates capacitor model, as shown in Fig. 4.19. The capacitance between these two parallel conducting plates is

$$C = \frac{\epsilon_0 \epsilon_{air} A}{D} \quad (4.2)$$

where ϵ_0 and ϵ_{air} is the dielectric constant of vacuum and air respectively, A is the surface size for electrostatic force analysis (area of overlap between the plates) and D is the effective electro-spacing between the two plates. For this model, D equal to the air gap separation distance because dielectric constant of air is 1. The two-plate capacitor model is modified to represent a typical slider-disk interface. Besides having air as the only insulating material, additional insulating materials such as the Diamond Like Coating (DLC), bonded lube and free lube are added onto the modified model, as illustrated in Fig. 4.20. Thus, the capacitance at the slider-disk interface becomes

$$C = \frac{\epsilon_0 \epsilon_{air} A}{\text{Effective_electro-spacing}, D} = \frac{\epsilon_0 \epsilon_{air} A}{\frac{d_{slider}}{\epsilon_{DLC}} + \frac{d_{air}}{\epsilon_{air}} + \frac{d_{lube}}{\epsilon_{lube}} + \frac{d_{disk}}{\epsilon_{DLC}}} \quad (4.3)$$

where d_{slider} , d_{air} , d_{lube} and d_{disk} are the material thickness of slider's DLC layer, air gap layer, lubricant layer and disk's DLC layer respectively; ϵ_{DLC} ϵ_{lube} is the dielectric constant of DLC and lubricant respectively. By observing the lower term of equation (4.3), the effective electro-spacing, D is seen to be influence by the material dielectric constant, i.e., material thickness can be very thick but its effective electro-spacing can be effectively reduced if its dielectric constant is large enough. Thus, the material electro-spacing can be derived as shown in equation (4.1).

Fig. 4.19. Two parallel conducting plates capacitance model.

Fig. 4.20. A modified capacitance model to represent a typical slider-disk interface.

The total effective electro-spacing when the slider is flying at 800 rpm is estimated based on equation (4.1) and the result is shown in Table 4.4. The effective electro-spacing for the disk without lube, with bonded lube and free lube is estimated to be 12.13 nm, 12.6 nm and 13.31 nm respectively. The difference in the effective electro-spacing between the disk without any lube and the disk with bonded lube or free lube are 4 % and 10 % respectively. These differences would cause the stiffness of the head-disk interface to be altered, i.e., changes in the second harmonic vibration amplitudes. The effect on the 2nd harmonic vibration amplitude due to these differences in effective electro-spacing between the slider and disk conducting layer can be clearly seen in the result shown in Fig 4.18. A larger 10% difference of

effective electro spacing has resulted in much lower 2nd harmonic vibration amplitude than the 4 % difference of effective electro spacing.

Table 4.4.

Electro-spacing estimation

Material Location	Material Layer	Material Layer thickness (nm)	Dielectric constant[#]	Effective Electro-spacing (nm)
Slider	DLC	20	3.2	6.25
Slider	Lube	0.8	1.7	0.47
Air-gap	Air	4	1	4
Disk	Lube	0.8 (Bonded Lube); 2.0 (Free Lube)	1.7	0.47 (Bonded Lube); 1.18 (Free Lube)
Disk	DLC	4.5	3.2	1.41

[#] Dielectric constant value are based on [35].

4.3 Relative ranking of surface interaction forces

An experiment is specially designed by the author and the team in an attempt to determine the relative ranking of the surface interaction forces present at the slider-disk interface. The three surface interaction forces are mainly the intermolecular force, the lube-induced meniscus force and the electrostatic force. Surface or contact potential that is present at the slider-disk interface contributes to the attractive electrostatic force. As mentioned in section 3.2, this contact potential value can be determined by applying the 2nd harmonic vibration method. The measured contact potential value is usually 0.2~0.3 V [30], too small to contribute to a large attractive force at the slider-disk interface. The measured contact potential values for various parameters are shown in the results in section 4.1. This contact potential value can be successfully offset by applying an equal but opposite dc voltage across the slider-disk interface, i.e. $V_{dc} = -V_{con}$. By doing so, the electrostatic attraction due to contact potential effect is removed from the slider-disk interface. This leaves the slider-disk interface with the two other surface interaction forces, i.e. intermolecular forces and lube-induced meniscus forces.

Fig. 4.21. Definition of asperities contact level.

In order for the intermolecular forces and lube-induced meniscus forces to co-exist at the slider-disk interface, the spacing between the slider and the disk surface must be near the asperities contact level, i.e., very small flying height. Fig. 4.21 schematically illustrated the meaning of near asperities contact level. Only at such level, will intermolecular forces effect become significant enough and at the same time allow lubricant menisci bridges to form between the slider and disk surface to create lube-induced meniscus forces. Therefore, before conducting the experiment, a test is required to determine the rotational speed and the magnitude of ac voltage (V_{ac}^2) that can allow the intermolecular force and lube-induced meniscus force to co-exist at the slider-disk interface. This test will require the rotational speed of the disk to be reduced to a low value to achieve small slider-disk spacing, and an increase in the ac voltage (V_{ac}^2) to a sufficiently large value to cause a large change in the slider's vibration. This will indicate that the slider is near the asperity contact level and possibly also indicate that lubricant menisci has formed under the slider surface too.

4.3.1 Test to determine near asperities contact level slider-disk spacing

This test is conducted with type D disk with free lubricant layer and slider B. The testing radius is again fixed at 38.10 mm and V_{ac}^2 is varied from 0.0625 V² to 4.0 V². The disk rotational speed is initially set at 2000 rpm and the slider is allowed to fly over the disk. The applied ac voltage is adjusted from a low value to a high value, i.e., V_{ac}^2 is increased from 0.0625 V² to 4.0 V². Amplitude of the 2nd harmonic vibration is measured at every applied V_{ac}^2 , and the result is recorded and shown in Fig. 4.22. The measured 2nd harmonic vibration amplitude is linear with V_{ac}^2 , the same trend as observed in chapter 4.2.1. In order to see a large change in slider vibration to indicate that slider is near asperities contact level, the slider-disk spacing has to be made

smaller by reducing the rotational speed. At 1000 rpm, no major difference is observed in the trend of second harmonic vibration amplitude versus V_{ac}^2 . However, when the rotational speed is reduced to 750 rpm, a special phenomenon occurs. As observed in Fig 4.22, when V_{ac}^2 is increased to 3.06 V, there is a large drop in second harmonic vibration amplitude from about 10 mV to 7 mV. The slider is left to fly over the disk for about 5 min and the 2nd harmonic vibration amplitude is observed to increase to 14.1 mV suddenly. Such phenomenon has been observed in many experiments, though it may not happen at the same voltage. This large drop in the slider 2nd harmonic vibration amplitude indicates that the slider is near the asperity contact level. Only at such a level, can the free lubricant then form menisci bridges between the slider and disk. Such a bridge provides damping to the slider which can reduce the slider 2nd harmonic vibration amplitude. The sudden increase in 2nd harmonic vibration amplitude after flying the slider for 5 min may be due to the shear force under the slider breaking the menisci bridge after prolonged flying.

Fig. 4.22. Second harmonic vibration amplitude for rotational speed at 2000 rpm, 1000 rpm and 750 rpm.

4.3.2 Experimental method to determine relative ranking of surface interaction forces

As mentioned before, the slider-disk spacing will be near asperity contact status if the rotational speed is reduced to 750 rpm. At such status, the intermolecular force and the lube-induced meniscus force can co-exist at the slider-disk interface. To determine which force is the dominant one, a specially designed experiment by the author and the team is carried out. This experiment requires flying the slider over a spinning disk at 750 rpm and applying increasing V_{ac}^2 until a large change in the slider 2nd harmonic vibration amplitude is observed. Subsequently, the rotational speed is increased and then reduced back to 750 rpm. V_{ac}^2 is again increased and changes in the 2nd harmonic vibration amplitude will be observed. The overall test cycle is shown in Fig. 4.23 and the experimental result is shown in Fig. 4.24.

Fig. 4.23. Overall test cycle for rotational speed versus time (top) and amplitude of V_{ac}^2 versus time (bottom).

Fig. 4.24. Record of the change in 2nd harmonic vibration amplitude for the overall test cycle (TC 1, TC 2, TC 3 and TC 4)

In the first test cycle TC 1, the rotational speed is fixed at 750 rpm. Applied ac voltage is gradually increased till a large change in the slider vibration occurs. From the results shown in Fig. 4.24, the slider 2nd harmonic vibration increases linearly with increasing applied voltage V_{ac}^2 at a gradient of about 7.3 mV/V^2 . However, when V_{ac}^2 reaches a value of 2.25 V^2 , there is a large reduction in the slider 2nd harmonic vibration from 11 mV to 7 mV. As mentioned earlier, this is the point that the slider is near the asperities contact level and lubricant menisci bridges have formed between the slider and disk surface. The lube-induced menisci will provide damping to the slider which reduces its amplitude of 2nd harmonic vibration. After observing a decrease in the slider's 2nd harmonic vibration, the amplitude of V_{ac}^2 is reduced immediately from 2.25 V^2 to 0 V^2 to avoid any strong slider-disk contact. If V_{ac}^2 is continue to increased, slider vibration will be higher and stronger slider-disk contact can be expected since the slider is already near asperities contact level. When V_{ac}^2 is reduced from 2.25 V^2 to 1.5 V^2 , the slider's 2nd harmonic vibration amplitude

does not return back to its original level of 13 mV. Instead, the slider's 2nd harmonic vibration amplitude remains low at about 6.5 mV. V_{ac}^2 continues to decrease linearly with the 2nd harmonic vibration amplitude at a lower gradient value of about 4.1 mV/V². This is because the lubricant menisci bridges are still forming at the slider-disk interface.

During the second test cycle TC 2, the rotational speed of the disk is increased to 1000 rpm and then reduced to its initial speed of 750 rpm. Subsequently, V_{ac}^2 is increased and slider 2nd harmonic vibration amplitude is recorded. By increasing the rotational speed, the shear force under the slider will be increased too. If the shear force is large enough to break the menisci bridge under the slider, the gradient of the slider's 2nd harmonic vibration amplitude versus V_{ac}^2 should resume to its original gradient of 7.3 mV/V². However, as shown in Fig. 4.24, the 2nd harmonic vibration amplitude does not resume to its original level. Instead, it remains low at a gradient of 4.1 mV/V². This shows that the attractive force caused by the menisci bridge that is formed below the slider still act on the slider and disk interface which damps out the slider's 2nd harmonic vibration. The rotational speed is then increased to 2000 rpm and reduced back to 750 rpm in the third cycle TC 3, in an attempt to create a large enough shear force to break the menisci bridge at the slider-disk interface. The testing procedure for TC 3, to acquire the slider's 2nd harmonic vibration is the same as TC 1 and TC 2. The result shows that the gradient of slider's 2nd harmonic vibration amplitude versus V_{ac}^2 still remains at the low level of 4.1 mV/V².

In test cycle 4, the rotation speed is further increased to a higher speed of 5000 rpm and then reduced back to 750 rpm. V_{ac}^2 is then increased and the slider's 2nd

harmonic vibration amplitude is measured and shown in Fig. 4.24. This time the gradient of the slider's 2nd harmonic vibration amplitude versus V_{ac}^2 has resumed its initial gradient of 7.3 mV/V^2 . This means that by allowing the rotational speed to reach 5000 rpm, there is a large enough shear force under the slider to break the menisci bridge at the slider-disk interface. The slider is no longer being held down by the lube-induced meniscus force, thus its 2nd harmonic vibration amplitude is increased.

4.3.3 Analysis of the experimental study

When the rotational speed is set at 750 rpm, the slider is flying at near asperity contact level. According to the experimental result shown in Fig. 4.24, increasing V_{ac}^2 to 1.5 V^2 will make the slider vibration stronger which reduces the slider 2nd harmonic vibration amplitude. Lubricant menisci bridges have possibly formed at the slider-disk interface. The slider asperities height as determined in the Glide Test in chapter 3.4.3 is estimated to be about 3.5 nm. The lubricant layer thickness is about 1~2 nm. That means that the slider flying height at near asperities contact is approximately in the range of 4~5 nm. At such low slider-disk spacing, beside having lube-induced meniscus force due to the formation of menisci bridges under the slider, intermolecular force will also exist at this slider-disk interface. Electrostatic force due to the contact potential is not considered in this slider-disk interface because it is offset by applying an equal but opposite dc voltage. Even if this contact potential value is not offset and included in the experiment, its measured value is just too small to cause any substantial electrostatic attraction force on the slider. Thus, through the process of elimination, only the lubricant-induced meniscus force and intermolecular force are left as the candidates for relative ranking of the surface interaction forces.

Using the experimental results from Fig. 4.24 as supporting data, the effect of lube-induced meniscus to cause the decrease in the slider 2nd harmonic vibration amplitude during test cycle 1 is found to be more dominant than the intermolecular force. If intermolecular force is the dominant force, when rotational speed is increased to 2000 rpm, the amplitude of 2nd harmonic vibration should resume its original level when rotational speed is reduced to its original speed of 750 rpm. This is because, at bigger rotational speed of 2000 rpm, the slider flying height increases too to about 10 nm (refer to Fig. 4.14a). With a higher flying height, intermolecular force became a lot weaker than with a flying height of 4~5 nm when rotational speed is initially at 750 rpm. This will allow the slider's 2nd harmonic vibration to return to its original level. But because the lube-induced meniscus force caused by the menisci bridges under the slider is more dominant than the intermolecular force, the slider's 2nd harmonic vibration is effectively suppressed by the lubricant meniscus force and thus unable to regain its original level. Therefore, in this experiment, lube-induced meniscus force is found to be the dominant force over intermolecular force as well as the electrostatic force caused by contact potential effect.

4.4 Summary

The harmonic vibration method has been applied to study the surface interaction forces experimentally in this chapter. A characteristics study of contact potential value at the slider-disk interface under various influences of different rotation speeds, different lubricant thicknesses, slider-disk contact and different lubricant structures has been done. The following summarizes the important results obtained from the contact potential studies which no similar observation been made yet based on the author's best knowledge:

1. The contact potential value presents at the slider-disk interface remains relatively constant under various rotational speeds, if the head-disk spacing is large enough and short range force effect is negligible. However, an increase in contact potential value is observed when slider-disk spacing becomes smaller as rotational speed is reduced to 1000 rpm. This is due to additional tribo-charge built up between the slider-disk interface.
2. Thicker lubricant increases the contact potential value.
3. Contact potential initially decreases with the increase of slider flying duration over the disk surface. When the flying duration is long enough, the contact potential will stabilize at a constant value.
4. Contact between the slider and disk results in increasing contact potential value. Very light head-disk contact has very slight effect on its contact potential value.
5. Double-ended lubricant structure has higher contact potential value than single-ended lubricant structure. Single-ended lubricant gives unstable contact potential measurement while double-ended lubricant gives stable contact potential measurement.

A characteristics study of 2nd harmonic vibration at the slider-disk interface vibration under various influences such as air bearing stiffness, lube-induced meniscus and different electro-spacing has been done. The following summarizes the important results obtained from the slider second harmonic vibration studies:

1. Larger air bearing stiffness will lower the amplitude of 2nd harmonic vibration at the slider-disk interface.

2. The lubricant menisci that form between the slider and the disk surfaces provide additional damping to the slider-disk interface which effectively lowered the slider 2nd harmonic vibration amplitude.
3. Larger electro-spacing across the conducting layer of the slider and disk will result in reduced 2nd harmonic vibration amplitude of the slider. This is due to smaller electrostatic interaction at larger electro-spacing.

Lastly, efforts have been made in determining the relative ranking of surface interaction forces present at the slider-disk interface. The three surface interaction forces are mainly the intermolecular force, lube-induced meniscus force and the electrostatic force. Contact potential that contributed to the electrostatic force is usually very small (less than 0.2~0.3 V). This value is too small to have any significant contribution to the surface interaction force. Through the process of elimination, the surface interaction forces that could have significant effect on the slider disk interface are the intermolecular force and lube-induced meniscus force. Through a specially designed experiment as described in this chapter, the lubricant-induced meniscus force is found to be the dominant force over the intermolecular force.

CHAPTER 5

Slider-lubricant interaction and approaches toward stable interface

5.0 Introduction

When the slider is flying over a thin layer of lubricant at low flying height, there is certain level of interactions between the slider's air bearing surface and the disk lubricant layer. These interactions can displace the lubricant layer on disk surface and may even cause the lubricant to be transferred away from the disk surface to the slider. Lubricant displacement caused by the slider motion is driven by four main mechanisms, i.e., hydrodynamic effect (air bearing forces), van der Waals effect (intermolecular forces) and electrostatic pressures, as well as stress from air shear stress [37]. It is also found that lubricant on the disk can be transferred to the slider surface even without any slider-disk contact [41]. This is mainly caused by slider-assisted evaporation and condensation of the lubricant layer on the disk surface.

Many papers had reported the investigation of the lubricant displacement effect caused by the slider motion. This chapter will focus on exploring the lesser-known effect of the slider-lubricant interaction, which is the lubricant transferring phenomenon at the slider-disk interface. In this chapter, an attempt has been made to study the effect of different slider's air bearing surface designs on the lubricant transfer at the head-disk interface. Since slider-lubricant interaction will lead to lubricant transferring, the amount of lubricant transferred can therefore be a good

indication of the intensity of slider-lube interaction. Using this idea, the intensity of slider-lubricant interaction could be investigated under different slider's air bearing surface parameters. Femto form-factor sliders of about 3.5 nm designed flying height with different trailing pad sizes are used for investigating the relationship between pad size and lubricant transferring. A possible design strategy is also explored and presented, aimed at minimizing the amount of lubricant transferred.

5.1 Slider selection and disk preparation

In order to study how different air bearing surface (ABS) parameters of a slider could affect the slider-lubricant interaction, sliders with different ABS designs have to be used. The selected sliders must also be of the same physical dimension to allow fair comparison between the different slider's ABS. Two types of femto-form factor sliders of same physical dimension but each with its own unique air bearing surface (ABS) design are selected to use in this experiment.

Femto form-factor slider refers to a slider with a physical dimension of only 0.85 mm x 0.70 mm x 0.23 mm (L x W x H). The first femto slider used, known as the Panda III slider, is designed and fabricated in Data Storage Institute (DSI). The other femto slider used in this experimental study, known as the INSIC slider, is designed by the Information Storage Industry Consortium (INSIC). INISC has always been at the forefront in technology in achieving extremely high areal density magnetic recording. The slider they designed has been demonstrated to achieve a very low flying height of 3.5 nm, though the flying height of this type slider varies a lot when it flies at different radii of disk. Thus, this type of slider is used as a reference to the DSI slider.

Figure 5.1 shows their respective air bearing surfaces. Panda III sliders are designed with a smaller trailing edge pad whilst the INISC type of sliders has a larger trailing edge pad.

Small spacing between the slider and disk surface is required in order to make slider-lubricant interaction more obvious. Thus, the disk used in this experimental study must be of a low gliding height of less than 3.5 nm, in order to achieve a flying height of around 3.5 nm. According to sections 3.4.3 and 3.4.4, disk sample B has a low surface roughness of 0.18 μm and passes the 3.5 nm glide height test. Thus, this type of disks, lubed with Z-Tetraol, is selected for the experimental study. The overall disk fabrication process is already described in chapter 3.4. The disks are step lubed, as shown in Fig 5.2, for lubricant transfer study. Normally, for a fully lubed disk, the lubricant on top of the disk consists of two layers, i.e., a bonded lube layer and a free lube layer. The free lube layer could be removed from the disk surface by rinsing with solvent. However, bonded lube layer has a strong affinity to the disk surface, thus cannot be easily removed by using solvent. Therefore, in order to produce a step lube coating pattern on the disk surface, half side of the disk will be dipped in a solvent (HFE-7200) to remove the free lube layer. The bonded lube layer, because of its strong affinity to the substrate surface, will be left on the disk surface after the rinsing process. This will leave half of the disk with free lubricant with bonded lube underneath and the other half with bonded lubricant only. All the disks are then scanned with the Optical Surface Analyzer (OSA) before the test to confirm the uniformity of lubricant distribution on the disk surface.

When the slider is flown over the step lubed disk, slider-lube interaction will make the free lubricant in the free lube region transferred to the slider, and then, to the bonded lube only zone. This is because vapor pressure is higher in the free lube region than the bonded lube region. Such a vapor pressure difference will cause a net lube transfer from the free lube region to the bonded lube region through the evaporation and condensation process [40].

Fig. 5.1. Panda III slider (left) and INSIC slider (left) ABS design. Green color part is the surface nearest to the disk surface. Trailing edge refers to the right end of the slider in this illustration

Fig. 5.2. Step profile lubricated coating pattern.

5.2 Experimental setup and process

The experimental setup in Fig. 3.5 is modified for the experimental study in this chapter. The modified experimental platform to study the lubricant transferring phenomenon is schematically illustrated in Fig. 5.3. It consists of a Head-Disk Testing Stand, a Head Gimbal Assembly (HGA) face-down jig and an Acoustic Emission (AE) sensor. The AE sensor is mounted onto the HGA jig to detect any head-disk contact. The AE signal is recorded using a Digital Oscilloscope. At first, basic flyability test is conducted using the prepared step pattern lubricated disks. The sliders tested as shown in Fig. 5.1, are loaded onto the disks at a velocity of 39 m/s and 0 skew angle.

Fig. 5.3. Schematic of experimental platform for lube transferring.

The simulation results of the two types of femto sliders are summarized in Table 5.1. After flying for a certain period of time, the slider is unloaded from the disk surface. The disk is then moved to Optical Surface Analyzer (OSA) for lubricant analysis. Subsequently, the disk is mounted back to the Head-Disk Testing Stand and the same slider is loaded back onto the same track to continue the testing process. The process of loading/unloading of slider and analyzing with OSA is repeated until 60 min interval is reached. Table 5.2 shows the total duration of flying. During the entire experiment, no detectable slider-disk contact occurs according to the output from the highly sensitive AE sensor.

Table 5.1.

Slider flying height and attitude under testing conditions (39m/s, 0° skew angle)

Slider Parameters	Panda III slider	INSIC slider
Flying Height (nm)	5.83	6.72
Pitch angle (μ rad)	133.0	327.3
Roll angle (μ rad)	-9.5	6.5

Table 5.2.

Slider cumulative flying duration

No. of time	Flying duration (min)	Cumulative Time (min)
1	2	2
2	4	6
3	6	12
4	8	20
5	10	30
6	10	40
7	10	50
8	10	60

5.3 Experimental results

Various techniques and measurement tools are available today for lubricant thickness analysis on a disk surface. They include Fourier-transform infrared spectroscopy (FTIR), electron spectroscopy for chemical analysis (ESCA), secondary ion mass spectroscopy (SIMS) and ellipsometry. There are good correlations among these lubricant thickness analysis tools. They are, in fact, often used concurrently as a means to cross-check thickness. However, one of the primary weaknesses of these techniques is their area of sampling - usually a few mm in diameter. Extrapolation of these values to the average lubricant thickness of a full disk can be a very time consuming and tedious measurement process. Technique that can allow measurement of lubricant thickness distribution over a larger area is thus required. Currently, the only measurement tool that allows fast measurement of lubricant distribution of the entire disk surface is the Optical Surface Analyzer (OSA) made by Candela Instruments. This measurement tool combined the following functions into one equipment: high-speed ellipsometer, reflectometer, scatterometer, and Kerr effect microscope. The ellipsometer in the OSA can run at very high sampling rate of up to 16 MHz which allows high speed imaging of the disk lubricant across the disk surface. The OSA can even measure lubricant thickness as small as 1 angstrom (high resolution). Thus, with all these advantages, the OSA is selected to be used in this experiment for capturing the lubricant distribution over the disk surface.

The OSA is used to scan across the step lubricated disk as illustrated in Fig. 5.4a. A typical OSA image of lubricant distribution after the slider has flown over the disk surface for 25 min is shown in Fig. 5.4b. An obvious trace left by slider flying over the track can be seen in this figure. This is where slider-lube interaction has taken

place. Region A and B has a layer of free lubricant and a bonded lube layer underneath; region C has a layer of bonded lube only. Θ is in the circumferential/ angular direction of the disk from 0° to 360° and R is in the radial direction of the testing zone from 33.3 mm to 35.3 mm.

Fig. 5.4. (a) Image of step lubricated disk with Radius, R and Angle, Θ defined. (b) OSA image of disk surface after 25 min of flying with INSIC slider.

Fig. 5.5 shows the OSA lubricant reflectivity in region B after 60 min of flying with Panda III slider and INSIC slider respectively. The OSA lubricant reflectivity signal shown in Fig. 5.5 is used to indicate lubricant thickness level. The reflectivity signal has an inverse relationship with the lubricant thickness. The larger peak area of the INSIC slider's curve means more lubricant being removed from region B than that from the Panda III slider. The area size between original lube reflectivity curve (before flying the slider over disk) and the actual curve obtained after each testing interval is calculated. The area size is proportional to the amount of removed lubricant in region B. Similarly, the same method is used to determine the relative amount of lubricant transferred for region A. The total cumulative amount of lubricant transferred for region A and B as a function of flying time is plotted out in Fig. 5.6. The result suggested that the INSIC slider moves more lubricant away from the lubed disk surface than the Panda III slider.

Fig. 5.5. OSA lubricant reflectivity signal curve of region B after 60 min of flying with Panda III slider (left) and INSIC slider (right).

Fig. 5.6. Cumulative amount of lubricant transferred away from mobile lube region for the entire 60 min of flying.

Fig. 5.7. Captured AE signal after one disk revolution for Panda III slider (left) and INSC slider (right).

During the entire test, the AE signal is carefully monitored to observe any slider-disk contact occurrences. Figure 5.7 shows a typical AE signals plot for one disk revolution that is captured during the tests with the Panda III and the INSC sliders respectively. In the event of slider-disk contact, a large AE signal of approximately

more than 0.5 V should be observed. Thus, no signs of slider-disk contact are observed in this experiment since the AE signals are all below 0.1 V, as observed in Fig. 5.7. The standard deviation of the AE signal for the panda III slider (17.3 mV) is slightly larger than that for the INSIC slider (16.4 mV). This is because, the INSIC slider is allowed to fly slightly higher than Panda III slider according to the simulation results in Table 5.1. A higher flying height means less interaction between the slider and disk surface. Thus, the standard deviation of the AE signal of the INSIC slider is slighter lower than Panda III slider. By having the INSIC slider fly higher than the Panda III slider gives the Panda III slider an advantage in terms of the amount of lubricant transferred. For example, if both sliders have the exact same ABS design, the one flying lower will have higher slider-lube interaction and thus leads to a larger amount of lubricant transferred across the slider-disk interface. In the actual experiment conducted, both the Panda III slider and INSIC slider have very different ABS design parameters. If INSIC slider is found to have a higher amount of lubricant transferred even when it is flying higher than the Panda III, it will mean that the different ABS design parameters is the main cause of the difference in the amount of lubricant transferred.

The result in Fig. 5.6 indicates that the INSIC slider transferred more lubricant away from the free lube region on the disk than the Panda III slider. After 60 min of flying, INISC slider and Panda III slider have caused about 1650 arbitrary unit (a.u.) and 600 arbitrary unit (a.u.) of lubricant respectively to be transferred away from the free lubed region on the disk surface. INSIC slider has transferred 1050 arbitrary unit (a.u.) or 160 % more of lubricant than Panda III slider after the entire 60 min of testing. This happened even when the INSIC slider is allowed to fly higher than the

Panda III slider (refer to Table 5.1). Therefore, the difference in the amount of lubricant transferred between both sliders is shown to be due to their respective differences in ABS design parameters.

5.4 Modeling of lubricant transferring at head-disk interface

In the previous experimental shown in chapter 5.3, the INSIC slider has been observed to transfer 1050 arbitrary units (a.u.) or 160 % more of lubricant away from the free lube region than the Panda III slider. Their differences in air bearing surface (ABS) design parameters is believed to cause the difference in the amount of lubricant transferred. In order to verify this explanation, a simplified model to describe the lubricant transferring at the slider-disk interface is created. This model is schematically illustrated in Fig. 5.8.

Fig. 5.8. A simplified model that schematically illustrates transfer of lubricant at the slider-disk interface

There are four main components that contribute to the amount of lubricant removed by the slider. Lubricant diffusion is assumed to be negligible as the evaluation process lasts only several hours. This amount of time is not sufficient to cause any significant lubricant diffusion. In general, the four main components are the condensation of lubricant from disk onto slider (Q_{cond}); the shearing of lubricant to the trailing ends of slider ($Q_{shear-slider}$); the evaporation of lubricant from slider (Q_{evap}) to disk and the shearing of lubricant on the disk surface ($Q_{shear-disk}$). At steady state, the inflow of lubricant to the slider-disk interface will be equal to the outflow from the slider-disk interface. Thus lubricant transfer's component of the slider can be expressed as [43]

$$Q_{cond} = Q_{shear-slider} + Q_{evap} \quad (5.1a)$$

And the lubricant transfer's component of the disk can be expressed as

$$Q_{cond} = Q_{shear-disk} + Q_{evap} \quad (5.1b)$$

The slider-disk spacing in this investigation is less than 10 nm. The mean free path of air at 1 atm of atmospheric pressure is 63.5 nm. Since the slider-disk spacing is smaller than the mean free path of air, the volumetric flow rates of lubricant on slider Q_{cond} and Q_{evap} can thus be expressed as [43, 44]

$$Q_{cond} = \frac{AP_0}{\rho} \sqrt{\frac{M_n}{2\pi RT}} * \exp\left[-\frac{\Pi(t_d)M_n}{\rho RT}\right] \quad (5.2)$$

$$Q_{evap} = \frac{AP_0}{\rho} \sqrt{\frac{M_n}{2\pi RT}} * \exp\left[-\frac{\Pi(t_d)M_n}{\rho RT}\right] \quad (5.3)$$

The volumetric flowrate of lubricant on slider surface due to shearing effect associated with slider can be expressed as [43, 44]

$$Q_{shear-slider} = \frac{av\eta_a}{2h\eta_{ls}} * t_s^2 \quad (5.4a)$$

and the volumetric flowrate of lubricant on disk surface due to shearing effect associated with slider can be expressed as

$$Q_{shear-disk} = \beta * Q_{shear-slider} = \beta \frac{av\eta_a}{2h\eta_{ls}} * t_s^2 \quad (5.4b)$$

where t_d and t_s are the lubricant thickness on disk and slider surface respectively, η_a is the air viscosity, η_{ls} is lube effective surface viscosity on slider surface, $\Pi(t)$ is the disjoining pressure for lubricant thickness t , A is effective slider area, ρ is lubricant density, T is the absolute temperature, P_0 is bulk vapor pressure, M_n is molecular weight, and R is the gas constant. The effective slider area A is roughly equal to the product of a and b , as illustrated in Fig. 5.9a, where a is the slider trailing pad width and b is the effective trailing pad length. Referring to Fig. 5.9b, the expression for b can be obtained as follows [42]

$$b = h \int_0^{L \cos(\varphi)} \frac{dx}{z} \approx \frac{h}{\varphi} \ln \left(1 + \frac{L\varphi}{h} \right) \quad (5.5)$$

where h is the slider flying height (FH), L is the trailing pad length and φ is the slider pitch angle. β is the fraction of time that the disk lubricant experiences slider shearing and it is simply the ratio of $b/(2\pi r)$ where b is the slider effective trailing pad length and r is the test radius of disk. From the simulation result shown in Table 5.1, Panda III flying height (h) and pitch angle (φ) are 5.80 nm and 133 μ rad respectively; INSIC slider flying height (h) and pitch angle (φ) are 6.70 nm and 327.3 μ rad respectively. As shown in Fig. 5.1, the sliders' trailing pad dimensions are measured and calculated based on equation (5.5). Panda III slider's trailing pad width (a) is measured to be 80 μ m and its effective trailing pad length (b) calculated to be 42.70 μ m. The INSIC slider's trailing pad width (a) is measured to be 100 μ m and its effective slider length

(b) calculated to be 61.10 μm . Fig. 5.9a summarizes both the sliders' trailing pad dimensions.

(a)

Fig. 5.9. (a) ABS view of Panda III slider and INSIC slider. (b) Side view of the trailing pad of a typical slider.

5.5 Result discussions

In order to compare the lubricant transferring performance of the two sliders, some assumptions are made to simplify the analysis. The diffusion of the lubricant is not considered during the several hours of testing. The lubricant thickness on the disk surface t_d and slider surface t_s are assumed to be identical for the two sliders during the tests. To determine the effect of different slider parameters such as the slider effective area (A), the slider's trailing pad width (a) and the effective slider trailing pad length (b) on the intensity of slider-lubricant interaction, the ratio of the amount of lubricant transfer due to different lubricant transferred components are calculated for both the INSIC and Panda III slider. The ratio of the amount of lubricant transfer due to condensation on both the INSIC slider and Panda III slider is

$$\begin{aligned} \frac{Q_{cond_INSIC}}{Q_{cond_PandaIII}} &= \frac{A_{INSIC}}{A_{PandaIII}} * \frac{\frac{P_0}{\rho} \sqrt{\frac{M_n}{2\pi RT}} * \exp\left[-\frac{\Pi(t_d)M_n}{\rho RT}\right]}{\frac{P_0}{\rho} \sqrt{\frac{M_n}{2\pi RT}} * \exp\left[-\frac{\Pi(t_d)M_n}{\rho RT}\right]} \\ &= \frac{A_{INSIC}}{A_{PandaIII}} = \frac{(a \times b)_{INSIC}}{(a \times b)_{PandaIII}} = 1.79 \end{aligned} \quad (5.6)$$

The ratio of the amount of lubricant transfer on the slider surface due to shearing effect is

$$\begin{aligned} \frac{Q_{shear-slider_INSIC}}{Q_{shear-slider_PandaIII}} &= \frac{\left(\frac{a}{h}\right)_{INSIC}}{\left(\frac{a}{h}\right)_{PandaIII}} * \frac{\frac{v\eta_a t_s^2}{2\eta_{ls}}}{\frac{v\eta_a t_s^2}{2\eta_{ls}}} \\ &= \frac{\left(\frac{a}{h}\right)_{INSIC}}{\left(\frac{a}{h}\right)_{PandaIII}} = 1.08 \end{aligned} \quad (5.7)$$

The ratio of the amount of lubricant transfer on the disk surface due to shearing effect is

$$\begin{aligned} \frac{Q_{shear-disk_INSIC}}{Q_{shear-disk_PandaIII}} &= \frac{\left(\beta \times \frac{a}{h}\right)_{INSIC}}{\left(\beta \times \frac{a}{h}\right)_{PandaIII}} * \frac{\frac{v\eta_a t_s^2}{2\eta_{ls}}}{\frac{v\eta_a t_s^2}{2\eta_{ls}}} = \frac{\left(\beta \times \frac{a}{h}\right)_{INSIC}}{\left(\beta \times \frac{a}{h}\right)_{PandaIII}} \\ &= \frac{\left(\frac{b}{2\pi r} \times \frac{a}{h}\right)_{INSIC}}{\left(\frac{b}{2\pi r} \times \frac{a}{h}\right)_{PandaIII}} = \frac{\left(b \times \frac{a}{h}\right)_{INSIC}}{\left(b \times \frac{a}{h}\right)_{PandaIII}} = \frac{(A/h)_{INSIC}}{(A/h)_{PandaIII}} = 1.55 \end{aligned} \quad (5.8)$$

From equation (5.6), it can be observed that the influence of the slider effective area, A on the intensity of slider-lubricant interaction is obvious. It shows that INSIC slider has an effective slider area that is 79 % bigger than the Panda III slider and can transferred 79 % more lubricant from the disk surface to the slider surface. Similarly as shown in equation (5.8), the effect of larger slider effective area on the intensity of slider-lubricant interaction can be observed even though their slider flying height is dissimilar, i.e. the INSIC slider flying higher than Panda III slider according to the simulation result in Table 5.1.

According to equation (5.4b), a larger slider flying height, h will reduce the amount of lubricant that is being transferred across the disk surface. However, equation (5.8) shows that even though INSIC slider has a larger flying height (6.72 nm) than Panda III slider (5.83 nm), the larger effective slider area of INSIC slider can still displaced 55 % more lubricant across the disk surface than the Panda III slider which has a smaller effective slider area. As mentioned earlier in chapter 5.4, when a higher flying height slider is compared with a lower flying height slider, because of weaker slider-

lubricant interaction for the higher flying height slider, it will transfer less lubricant. However, in this case, INSIC slider could transfer away more lube from the disk surface than Panda III slider even when it is flying higher. This has shown that the INSIC slider's ABS design parameters have a greater effect on the amount of lubricant transferred even though it has a flying height disadvantage over Panda III slider, i.e., higher flying height.

From equation (5.7), it is observed that about 8 % more lubricant gets accumulated at the trailing end of the INSIC slider than the Panda III slider due to the shearing effect on the slider surface. Although the influence of the slider trailing pad width (a) may seem to have little effect on the intensity of slider-lubricant interaction (only 8 % difference), the actual amount of lubricant that get accumulated at the trailing end of the slider may be even higher. This is true when considering the amount of lubricant that gets transferred on the slider due to condensation according to equation (5.6). This amount of lubricant that condenses on the slider surface coupled with the shearing effect under the slider surface will cause even more lubricant to be accumulated at the trailing end of the slider.

According to equation (5.1), the total amount of lubricant that is transferred away from the disk surface to the slider through condensation (Q_{cond}) equals to the sum of the amount of lubricant that gets accumulated at the slider's trailing end ($Q_{shear-slider}$) and the amount of lubricant that get evaporated from the slider surface back to the disk surface (Q_{evap}). That means, only a portion of the lubricant that get transferred to the disk surface will be transferred back to the disk surface through evaporation. The remaining portion of the lubricant will get accumulated at the trailing end of the slider

due to the shearing stress under the slider. This accumulated lubricant will contribute to the total amount of lubricant that is removed from the disk surface at steady state. From the comparisons expressed in equation (5.6) and (5.7), it is clear that the more lubricant that get transferred from the disk surface to the slider surface through condensation, the more lubricant will accumulate at the slider trailing ends. At least, a part of the accumulated lubricant cannot be transferred back to the disk surface through evaporation as seen in equation (5.1). Therefore, the INSIC slider will remove more lubricant from the disk surface as a result of having more lubricant accumulation at its trailing ends than the Panda III slider. This agrees with the experimental findings.

From the comparison expressed in equation (5.7), more lubricant is seen to be removed by the INSIC slider from the lubed region on the disk surface. Similar observations are seen in the experimental results. As mentioned earlier in the comparison shown in equation (5.7), apart from having dissimilar slider flying height, the behavior of the sliders on removing lubricant from the lubed disk surface is closely related to the effective slider area (A) which is roughly the value of $a \times b$. Therefore, an effective strategy to minimize the lubricant transfer is to reduce the slider effective length (b) and width (a), which is directly related to the slider trailing pad size.

5.6 Summary

Slider-lubricant interaction is studied quantitatively by determining the relative amount of lubricant transferred by a slider from a lubed disk surface. Two different Femto form-factor sliders are used in this study to compare their lubricant transferring characteristics against each other. The relationship between slider-lubricant interaction which is indicated by the amount of lubricant transferred and the slider air bearing surface design parameters is identified. An effective strategy to reduce slider-lubricant interaction and lubricant transferred is also explained in this study. It involves reducing the slider effective length and width, which are directly related to the size of the slider trailing edge pads. The above discussion is based on a simplified static model with various assumptions to make analysis possible at the present stage. In the future, a more accurate quantitative analysis could be made possible by including parameters such as slider air bearing pressure distribution, slider flying height modulation, lubricant film thickness modulation, etc into the model.

CHAPTER 6

Effect of Electrostatic Force on Slider-Lubricant Interaction

6.0 Introduction

As areal density continues to strive towards 1 Tb/sq² and beyond, slider-disk spacing has to be reduced to 2.5~3.5 nm. At such narrow slider-disk spacing, light slider-disk contact is unavoidable which can cause tribo-charge/emission at the head-disk interface. Electrostatic force due to this tribo-charge will cause the slider to be attracted towards the disk thus reducing flying height and increase head-disk interaction. This could result in an unstable head-disk interface and even catastrophic head crashes. Therefore, it is important to have a good understanding of the relationship between the electrical charge/potential built up and its effects on the slider-disk system.

In previous chapter 5, the amount of lubricant that gets transferred away from the disk surface under a flying slider is used as an indication on the intensity of slider-lubricant interaction. The same concept is applied in this chapter to determine the effect of electrostatic force on slider slider-lubricant interaction. In this chapter, experiment investigations are conducted to compare the intensity of lubricant transferring under different applied voltages but at the same slider flying height. Applying different voltages into the slider-disk interface would create different level of electrostatic force

conditions. Bump disks are used to calibrate the slider and ensure the consistency of flying height under different experimental conditions. Results indicate that the slider-lubricant interaction can be increased significantly when sufficient interface voltage is present at the head-disk interface. The amount of lubricant transferred across the head-disk interface is found to increase with the increase in the applied interface voltage.

6.1 Technique to ensure flying height consistency at different electrostatic force conditions

It has been reported that sufficiently high electrostatic force will cause significant reduction in the flying height of slider [29]. In order to achieve a fair comparison between different electrostatic force conditions, a technique has been introduced to maintain the same flying height under different testing electrostatic force conditions. This will help to determine whether the interaction remains constant when the slider-disk interface is under different interface voltages but at the same flying height. This technique would require conducting a flying height calibration on the test slider at different values of the applied interface voltage.

6.1.1 Flying height calibration principle and procedure

A laser bumped disk with the bump height of approximately 6 nm — as measured using Atomic Force Microscopy (AFM) — is used for the flying height calibration. Fig. 6.1 shows the AFM image of the measured track of the bumped disk. As mentioned before, different electrostatic force (different applied interface voltage) will lead to different flying height. Also, different slider flying speed (different disk rotational speed) will give different flying height. Therefore, flying height change

caused by electrostatic force can be compensated by adjusting the slider flying speed. The basic principle of flying height calibration involve applying different electrostatic force conditions onto the slider-disk interface and allowing the slider flying speed to be adjusted to a value which the slider just begin to contact the bumps on the laser bumped disk. At this flying speed, the slider-disk spacing will be identical to the bump height under the same electrostatic force condition. Thus, regardless of the different electrostatic force conditions applied to the slider-disk interface, the same slider-disk spacing can still be maintained identical by flying the slider at the speed at which the slider just begin to contact the bumps.

Fig. 6.1. Surface profile of the laser bumped track captured using AFM.

Fig. 6.2. Test slider's Air Bearing Surface (ABS) layout

The flying height calibration of the slider is carried out by first allowing the test slider, as shown in Fig. 6.2, to fly on a 6 nm high laser bump track located at radius of 17.98 mm under different electrostatic force conditions. The different electrostatic force conditions are created by applying different interface voltages such as 2 V, 1 V and 0 V, across the slider-disk interface. The experimental platform used here is the same as the one illustrated in Fig 3.4. The harmonic vibration method mentioned in chapter 3.2 is applied to determine the contact potential value at the slider-disk interface. The procedure to measure the contact potential value between the slider and disk has already been mentioned in chapter 4.1.3.

To ensure the accuracy of the test results, the electrostatic attraction effect caused by the contact potential between the slider and disk has to be removed or offset. The contact potential value can be offset by applying an equal but opposite dc voltage across the slider-disk interface according to chapter 3.2. The measured contact potential value is about -0.2 V to -0.3 V. The summation of contact potential and the applied dc voltage will give the absolute interface potential difference between slider and disk surface. For example, the contact potential between the slider and disk surface is measured to be -0.3 V. Therefore, by applying a dc voltage of 2.3 V, a 2 V of absolute interface potential between the slider and disk surfaces ($-0.3 \text{ V} + 2.3 \text{ V} = 2 \text{ V}$) will result; while the application of a dc voltage of 0.3 V gives the “true” zero interface potential of the head-disk interface ($-0.3 \text{ V} + 0.3 \text{ V} = 0 \text{ V}$).

6.1.2 Flying height calibration results on various electrostatic force conditions

The slider touch down operation was conducted by reducing the spindle velocity in step of 0.02~0.2 m/s. The slider touch down operation is a process where spindle velocity is reduced gradually to reduce the slider-disk spacing. When spindle velocity reaches a point when the slider's air bearing force is no longer able to fully lift the slider above the disk surface, contact between slider and disk will occur. This spindle velocity is where touch down occurs or known as the touch down velocity.

Before every touch down test, the test slider is cleaned with a solvent. This is to ensure that the slider surface is free from any lubricant or contaminants on its surface which can cause unreliable test results. The respective touch down velocity for the different applied interface voltage is determined by monitoring the output of Laser Doppler Vibrometer (LDV) signal. The LDV signal amplitude during slider touch down under different electrostatic force conditions, i.e., 2 V, 1 V, 0 V, are captured and shown in Fig. 6.3. Standard deviation of the LDV signal is also computed and plotted out in Fig. 6.4. The touch down speed for 2 V, 1 V and 0 V of electrostatic force conditions are 2300 rpm, 1940 rpm and 1800 rpm respectively at the testing radius of 17.98 mm. In terms of linear velocity, the touch down speed for 2 V, 1 V and 0 V will be 4.35 m/s, 3.7 m/s and 3.4 m/s respectively.

The slider touch down speed is initially assumed not to go below 1200 rpm. Therefore, a sampling duration of at least 45 ms ($1200 \text{ rpm} / 60 \text{ sec} = 0.045 \text{ sec}$) is used to ensure that there is enough time to capture signal for at least a complete disk revolution (see Fig. 6.3). The touch down point is determined when every part of the laser bump track

comes into full contact with the slider in a complete disk revolution as shown in Fig. 6.3. Before any slider-disk contact, the LDV signal amplitude is very low (<10 mV). During the event of a touch down, the LDV signal amplitude becomes at least 50 mV high. The result in Fig. 6.3 shows that the amplitude of LDV signal persisted throughout the entire disk revolution during slider-disk contact when the spindle velocity is at 4.35 m/s and 3.7 m/s and 3.4 m/s under applied interface voltages of 2 V, 1 V and 0 V respectively. Therefore, by flying the test slider at their respective velocities ensures that the flying height is consistent at approximately 6 nm.

Fig. 6.3. LDV signal captured during slider touch down operation at different electrostatic force conditions of 0 V, 1 V and 2 V.

Fig. 6.4. LDV standard deviation signal for different interface voltages during slider touch down operation at disk radius 17.98 mm.

6.2 Experimental study of electrostatic force on slider-lubricant interaction

Type D disk (refer to Table 4.1) lubed with a layer of PFPE lubricant is used for this study. Step-lubed disk pattern as illustrated in Fig 5.2 is specially prepared for this experiment to get quantitative comparison of lubricant transfer at same the flying height but different electrostatic field conditions. It is done by dipping half of the disk inside HFE-7200 solvent for 10 min to remove the top free lubricant layer. This will leave one half of the disk with a bonded lubricant layer and the other half with a free lubricant layer. The detailed preparation process of such a step-lubed disk has already been mentioned in chapter 5.1 All the disks are then scanned with the Optical Surface Analyzer (OSA) before the test to confirm the uniformity of lubricant distribution on the disk surface.

To determine the effect of electrostatic force on the intensity of slider-lube interaction, different value of absolute interface voltages of 2 V, 1 V and 0 V are applied to the

slider and disk interface. The test parameters are shown in Table 6.1. To achieve a fair comparison, the total linear distance that the slider flew over the disk surface is maintained the same at about 15.96 km. This is done by varying the flying duration for different electrostatic force conditions as different spindle speeds are used for different interface voltage conditions.

After the slider has flown over the disk on the required testing track, the disk is taken out from the Head-Disk Testing Stand and scanned with OSA for its lubricant distribution profile. The disk is then placed back onto the Head-Disk Testing Stand and testing is conducted on another track. Before flying the slider on the disk again, the slider is also cleaned with solvent to remove any contamination and lubricant pick-up on the slider surface. During the entire testing process, no contact between the slider and disk surface is observed as monitored by a highly sensitive AE sensor.

Table 6.1

Test parameters for different absolute interface potential difference at HDI

Test track	Testing Radius (mm)	Absolute interface Volt (V)	Calibrated velocity (m/s)	Actual velocity (m/s)	Spindle Speed (RPM)	Flying duration (min)	Flying distance (km)
1	25.40	+2.0	4.35	4.36	1640	61:00	15.96
2	30.48	0	3.40	3.42	1070	77:50	15.96
3	33.02	-1.0	3.65	3.67	1060	72:35	15.96
4	35.56	-2.0	4.35	4.36	1170	61:00	15.96

6.3 Results and Discussions

Fig. 6.5 shows a typical disk's lubricant distribution image captured using Optical Surface Analyzer (OSA) after the test slider flown over the test track for 61 min. Traces of the flying slider can be seen in this figure. Region A and region C has a layer of free lubricant and a bonded lube layer underneath; region B has a bonded lubricant layer only. θ is in the circumferential/ angular direction of the disk from 0° to 360° and R is in the radial direction of the testing zones.

Fig. 6.5. (a) Image of step lubricated disk with Radius, R and Angle, θ defined. (b) Typical OSA image after test slider has flown on Test Track 1 for 15.96 km with +2.0 V of interface voltage.

The OSA lubricant reflectivity signals for the different test tracks are captured from the typical OSA image, such as the image in Fig. 6.5. Fig. 6.6 shows the OSA lubricant reflectivity signals for all the different test tracks under different interface voltages captured from the OSA images as shown in Table 6.2. The amount of lubricant transferred at these test tracks is determined in order to indicate the intensity of slider-lube interaction. Region A and B give the amount of lubricant removed because it has a free lubricant layer. Region C gives the amount of lube transferred onto it because it has only bonded lubricant layer. The data processing process to determine the amount of lubricant being transferred or removed from the disk is similar to the data processing process mentioned in chapter 5.4. It involves computing the differences between the OSA lubricant reflectivity signal in Fig. 6.6 before and after testing to determine the amount of lubricant transferred.

After the data processing process, the relative amount of lubricant transferred across the slider-disk interface can then be determined. Fig. 6.7a shows the amount of lubricant removed from free lube region A and Fig. 6.7b shows the amount of lubricant transferred over to the bonded region B after testing with different interface voltages.

Fig. 6.6. (a) Lubricant distribution profile captured using OSA for Test Track 1, (b) Test Track 2, (c) Test Track 3 and (d) Test Track 4 under their respectively interface voltage of +2 V, 0 V, -1 V and -2 V respectively.

Table 6.2

Lubricant distribution images of Test Tracks 1, 2, 3 and 4 captured using OSA.

Test Track	Region A (Free Lube)	Region B (Bonded Lube)	Region C (Free Lube)
1 (+2 V)
2 (0 V)
3 (-1 V)
4 (-2 V)

(a)

(b)

Fig. 6.7. (a) Relative amount of Lube transferred away from free lubed region A
(b) Relative amount of Lube transferred to bonded lube region B.

Fig. 6.8. Relative amount of lube transferred away from free lube region A under applied interface voltage of 0 V and +2 V at 12 mV and 6 mV of LDV standard deviation signal respectively

From the results shown in Fig. 6.7a, it is clear that as the applied absolute interface potential is increased, the corresponding amount of lubricant transferred away from the disk surface increases even when the slider's flying height is kept the same. The amount of lubricant transferred under high interface voltage of ± 2 V is more than double the amount of lubricant transferred under only -1 V of interface voltage. This implies that when higher interface voltage is applied to the slider-disk interface, stronger slider-lubricant interaction occurs, thus, causing more lubricant to be transferred from free-lubed region to slider and bonded-lubed-only region.

In order to further confirm the experimental observation, another experiment is done by letting the 0 V case have the obvious advantage (lower flying height), over the +2 V case (higher flying height), i.e., the test slider under +2 V of applied interface voltage is allowed to fly higher than the case with 0 V of interface voltage. 0 V case has the advantage in terms of the amount of lubricant it can transfer when it is made to fly lower than the 2 V case. From Fig. 6.4, spindle speed of 1860 rpm at 12 mV of

LDV standard deviation signal is used for testing the 0 V case. To achieve a higher FH for the +2 V case, test speed at 2600 rpm with smaller contact intensity of only 6 mV of LDV standard deviation signal is used for testing. The flying distance is again kept the same at about 15.96 km for the 0 V and +2 V condition. After scanning with the OSA, the relative amount of lubricant transferred away from the free lube region A is determined and shown in Fig. 6.8. It can be observed that an interface voltage of +2 V can still cause stronger slider-lube interaction and more lubricant transferring even when its flying height is higher than the case with a 0 V interface voltage. The result is consistent with the earlier experiments, indicating that high interface voltage (2V), i.e., high electrostatic force, strengthens the intensity of the slider-lube interaction.

As discussed in chapter 5.5, lubricant can be transferred away from the disk surface through evaporation and condensation process. According to equation (5.2) and (5.3), the evaporation and condensation processes of the lubricant across the slider-disk interface are related to the lubricant disjoining pressure on the disk surface. Lubricant disjoining pressure is related to the Hamaker constant, and Hamaker constant is related to the ionization potential [4]. A sufficient electrical field might have altered the ionization potential which increases the lubricant volumetric flowrate due to evaporation and condensation. As a result, more lubricant transfer can occur under higher applied interface voltage. Lubricant degradation under a strong electrical field might be another reason that causes more lubricant to be transferred away from the disk surface [47]. However, further investigations on the bonded lube region B of Fig. 6.7b indicate that the amount of lubricant transferred to the bonded region increases with the increase in interface voltage. If lubricant is to be degraded during this short

period of test (<80 min) due to an applied electrical field, the corresponding amount of lubricant transferred to the bonded region under a larger interface voltage should be lesser than the smaller interface voltage. But the opposite happens here. Thus, it is assumed that the electrical field during this short period of testing will not cause a substantial amount of lubricant degradation. In other words, the possible lubricant degradation can not be considered as the main reason of lubricant transfer.

6.4 Summary

The effect of the electrostatic force on the slider-lubricant interaction has been studied. The intensity of the slider-lubricant interaction is determined by monitoring the amount of lubricant transferred on the disk surface of a specially prepared step-lubed disk. Different electrostatic force conditions have been tested by applying different interface voltage across the slider and the disk. In order to have a fair comparison between different electrostatic force conditions, the slider's flying height and slider flying distance are maintained the same for the different electrostatic force conditions by applying a technique that uses bumped disk calibration method. During the test, various interface voltages (2 V, 0 V, -1 V and -2 V) are applied across the slider-disk interface to create different level of electrostatic force. The disk is subsequently scanned with an Optical Surface Analyzer (OSA) to measure its lubricant distribution profile. The test results show that the intensity of the slider-lubricant interaction increases with increasing applied interface potential even when the flying height of the tested sliders are kept the same. This is evident from the observed increase in lubricant transfer from the free-lube region to the bonded-lube-only region of the disk.

CHAPTER 7

Conclusion

7.1 Summary and Conclusion

The magnetic disk drive is the dominant data storage device in modern society. Currently, more than 90% of disk drive failures are related to head-disk interface problems. In the quest to achieve higher areal storage density in hard disk drives, the physical spacing between the head and the disk has been reduced to a few nanometers. At such small head-disk spacing, short range surface interaction forces that were previously negligible in older hard disk drives have become a major concern. These interaction forces, which include the intermolecular force, the electrostatic force and the lubricant-induced meniscus force, are adhesive in nature and tend to drag the slider toward the disk surface. This can lead to contact vibration or even a head-disk crash. Therefore, it is important to understand these surface interaction forces in order to design a robust head-disk interface. Another potential area that can lead to unstable head-disk interface is the slider-lubricant interaction. This thesis has focused its investigation on the effect of surface interaction forces and slider-lubricant interaction through a series of carefully designed experiments. With the understanding of these effects, one can then design a more stable and robust head-disk interface.

A method, known as the Harmonic Vibration Method, is proposed in chapter 3 to investigate the effect of surface interaction forces. Experimental studies of the surface

interaction force are carried out in chapter 4 based on the 2nd harmonic vibration method. Characteristic study of contact potential value is first conducted. The author and the team observed for the first time that the contact potential value present at the slider-disk interface remains relatively constant under various rotational speeds; thicker lubricant can increase the contact potential value; contact potential will initially decrease with the increase of slider flying duration over the disk surface but will eventually stabilize; contact between the slider and disk increases the contact potential value and very light head-disk contact causes very slight changes on the contact potential value; a double-ended lubricant structure is unstable and has higher contact potential value than a single-ended lubricant structure. Secondly, a characteristic study of the 2nd harmonic vibration is also conducted and it is found that larger air bearing stiffness will lower the amplitude of 2nd harmonic vibration at the slider-disk interface; lubricant menisci that are formed between the slider and the disk surfaces provide additional damping to the slider-disk interface and can effectively lower the slider 2nd harmonic vibration amplitude; larger electro-spacing across the conducting layer of the slider and disk will result in lowering the slider 2nd harmonic vibration amplitude due to smaller electrostatic interaction at larger electro-spacing.

Studies of the surface interaction forces have been shown in many journal papers. Until now there is still no clear definition which surface force dominates. There are mainly two arguments, one that state that intermolecular force is the dominant force and another that states that meniscus force is the dominant effect. In an attempt to define which force is dominant, the author and his team had specially designed an experiment to study the surface interaction forces based on the proposed second

harmonic vibration method. A relative ranking of the short range surface interaction forces which include the intermolecular force, lube-induced meniscus force and electrostatic force is then obtained for the first time using the second harmonic vibration method. The typical contact potential value that contributes to the electrostatic force at the slider-disk interface is too small to have any significant contribution to the surface interaction force. Through the process of elimination, the surface interaction forces that could have significant effect on the slider disk interface are the intermolecular force and lube-induced meniscus force. After conducting a carefully designed experiment, it was found that lubricant induced meniscus force is the dominant force over the intermolecular force and electrostatic force.

Beside the short range surface interaction forces, slider-lubricant interaction is another potential area that could affect the stability of the head-disk interface. It has been studied in chapter 5 and 6. In chapter 5, slider-lubricant interaction is investigated by determining the relative amount of lubricant transferred by a slider from a lubed disk surface. This relative amount of lubricant transferred is used as an indication of the intensity of slider-lubricant interaction, i.e., the stronger the intensity of slider-lube interaction, the higher the amount of lubricant being transferred. The relationship between the intensity of slider-lube interaction and the slider air bearing design parameters, such as the trailing pad size, is identified. From the experimental results observed in chapter 5, a slider with a larger trailing pad size will tend to cause more lubricant transferring across the slider-disk interface. This will lead to stronger slider-lube interaction. An analytical model is also used to analyze the lubricant transferring phenomenon observed and it is found to correlate well with the experimental results. Therefore, based on the experimental results and the analytical model, the author

found that the slider-lubricant interaction can be effectively reduced by reducing the effective slider trailing pad area.

In chapter 6, the effect of electrostatic force on slider-lubricant interaction is studied. Based on the same methodology used in chapter 5, the intensity of slider-lubricant interaction is determined by observing the amount of lubricant transferred across the slider-disk interface. Previous journal papers had shown that the increased electrostatic force across the slider-disk interface would result in the amount of the lubricant transferred across the slider-disk interface to be increased as well. However, it was not clearly defined in these journal papers that the increased in lubricant transferred was due to the increased in electrostatic force or due to the reduced in slider flying height since increased electrostatic force will also cause stronger attraction of the slider to the disk surface too. Thus, the author used a bumped disk to calibrate the slider flying height. This will ensure the consistency of the slider flying height under different experimental conditions. From the obtained experimental results, it is observed that the effect of increasing the electrostatic force will lead to more lubricant transferring across the slider-disk interface. Since the slider is calibrated to have the same flying height throughout the experiment, it can be concluded that the increased in lubricant transferred is solely due to the increased in the electrostatic force and this increased in lubricant transferred is not caused by the reduction of slider flying height.

7.2 Recommendations and Future works

Lubricant-induced meniscus force is found to be the dominant adhesive force in this research work. Therefore, the amount of free lubricant on the disk should be controlled carefully to avoid a large amount of lubricant being transferred to the slider's surface. In chapter 5, the amount of lubricant transferred away from the disk surface is found to be effectively reduced with a smaller trailing edge pad. The use of a smaller trailing edge pad not only reduces the intensity of slider-lubricant interaction, but can also effectively reduce the amount of meniscus attraction forces as seen in [30]. In addition, the use of a smaller trailing pad can also effectively reduce the strength of the intermolecular force for the ultra-low flying slider [12]. Based on the electrostatic force equation for an inclined and horizontal plate (3.5), the electrostatic force is directly related to the area of the plate. Thus, if the area of the plate is made smaller, i.e., smaller trailing edge pad, the corresponding strength of electrostatic force will be reduced too. Therefore, the use of a smaller trailing edge pad is beneficial in reducing the surface interaction forces as well as the intensity of slider-lubricant interaction. In addition to using a smaller trailing edge pad, designing a stiffer air-bearing slider will be an added advantage to counter the attractive effect of the surface interaction forces especially with small slider-disk spacing.

In order to postpone the superparamagnetic limit to higher densities, next generation technologies such as Heat Assisted Magnetic Recording (HAMR) and patterned media recording are expected to be used. In HAMR, a laser light is shone onto the disk to heat up the individual magnetic bit cells, thereby lowering the media coercivity during the write process. The track where writing is taking place is heated and cooled rapidly. The lubricant is therefore required to withstand repeated

temperature changes from room temperature to above 300°C in a few nanoseconds. When lubricant is repeatedly heated to high temperature and cooled rapidly, its stability will become a main concern. Therefore, this research work can be extended to study the stability of the lubricant that is used for HAMR application. When the lubricant is heated up, the rate of evaporation and condensation will be increased and thereby affecting the amount of the lubricant transferred across the head-disk interface. This will also increase the intensity of slider-lubricant interaction and affect the stability of the head-disk interface. Thus, it will be beneficial to understand how the heated lubricant for HAMR application can affect the slider-lubricant interaction. And by understanding these problems, one can then explore new solutions or develop new types of lubricant that could reduce the intensity of the slider-lubricant interaction when the lubricant is heated to a high temperature.

In bit patterned media (BPM), the magnetic layer is created as an ordered array of highly uniform islands, each island capable of storing an individual bit. The entire volume of bit can then resist the effect of thermal agitation, thus enabling higher recording density. These individual bits are also physically separated from the neighboring bits in the circumferential as well as radial direction, thereby eliminating transition noise between adjacent bits. When the slider flies over the BPM, it “sees” the disk surfaces as individual island-like regions. The flying characteristic of a slider over such a surface is different from that over a conventional “smooth” disk. Therefore, the flying stability of the slider will be affected. Also, the surface interaction forces between the flying slider and the BPM will be different from those between the flying slider and a conventional “smooth” disk. For example, the way the lubricant menisci form between the individual island bit and the slider air bearing

surface will be different from the way lubricant menisci form between a smooth disk and a slider air bearing surface. This will affect the total adhesive strength at the head-disk interface. Thus, it will be beneficial to extend the present research work to study the surface interaction forces considering pattern media disk. By understanding the effect caused by patterned media on the surface interaction forces, one can then design a more stable and robust head-disk interface for future disk drives.

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