Modelling and experimental investigations of thermal-induced nano-deformation in ultra high density magnetic data storage systems

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**Modelling and Experimental Investigations of
Thermal-Induced Nano-Deformation in Ultra High
Density Magnetic Data Storage Systems**

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of doctor of philosophy

2010

Preface

It took me more than 8 years to complete this thesis, which is twice longer than a normal period for PhD study. I started my PhD research in November 2001. After three years of hard work, I made significant progress in studying the thermal-induced disk drive slider nano-deformation and its effect on disk drive performance, generated 7 papers in this research area. In fact, I was among the first batch of researchers working on this topic and this topic becomes rather hot in recent years. The thermal-induced nano-deformation study get evolution into thermal actuators which have been used in most of the new disk drive designs since 2008.

In order to support my parents and family, I accepted a job offer and joined Hitachi Global Storage Technologies (HGST) in 2004 and became a part-time student as I thought that I could continue my PhD work and thesis writing in the evening and weekend. My job in HGST was on disk drive failure analysis and root cause identification. The job was highly challenging and very interesting to me. In fact, I always stayed in HGST factory till 10 pm in the first 3 months of my career in HGST. After that, I was asked to take more responsibilities in the company, travel often overseas and take care of one task or product after another. Another factor was that an unexpected opportunity pushed me to a joint telecommunication business with one of my friends. As a result, I became even more occupied during my work hour, in the evening and during weekend. For the above reasons, my thesis work was greatly delayed until I resigned from HGST in 2008. With support of

my family and great encouragement all the years from my PhD supervisors, I eventually completed the thesis.

The research topic covered in the thesis was on thermal-induced disk drive slider deformation and flying height changes, which was in technology frontiers in 2001. My publications are among the frontier publications on the topic. In fact, the technology has been developed so fast that the thermal flying height control technology has been implemented in disk drives nowadays. I hope, the methods and results documented in this thesis are still valuable from the academic point of view.

Abstract

The continuously developing of hard disk drive (HDD) industry pushes the magnetic recording technology growth very fast over past 2 decades. The areal density of HDD is going to be bigger and bigger. The bigger areal density requires a smaller flying height (FH). The researchers are targeting to achieve the areal density of 1000 Gb/in², and one of the major technology challenge is to lower down the FH to 5 nm.

This thesis explores understanding and solutions for achieving highly stable head-disk interface for ultra-high density magnetic recording. It presents a systematic study on thermal induced nano-deformation and flying height change caused by such nano-deformation at ultra-low flying height. The study consists of three parts: 1) experimental investigations on the thermal induced slider nano-deformation and flying height changes; 2) analytical and numerical studies on write current induced temperature field in head-slider as well as the resultant body deformation; and 3) exploration of effective methods to minimize the FH changes caused by such thermal effect.

In order to understand the mechanism of the write current induced nano-deformation and FH change, analytical and numerical simulations are carried out. Firstly, the temperature distributions corresponding to the heat generated by the write current on the slider head are analytically calculated, taking into account the heat source location, the thermal properties of the slider head material and the heat transfer due to the airflows at the head-disk interface.

Then, the numerical simulations by commercial software ANSYS are conducted to check the analytically obtained temperature distribution, and most importantly, to obtain the thermally induced deformation of the head-slider. The results show that the write current indeed leads to large local protrusion around the read/write head. Further simulations on flying height changes are carried out by using the industry standard air-bearing simulation code. The simulation results are compared with the experimental data. It demonstrates that the thermal induced temperature rise in slider, the slider protrusions on ABS (air-bearing-surface) and the slider flying heights can be accurately predicted with proper thermal boundary conditions corresponding to the disk rotation conditions. The results also confirm that the maximum thermal effects on the slider occur around the write/read head which generates the Joule heat due to the write current.

The FH between the read/write head and disk surface depends on the air pressure distribution on the slider ABS. The write current induced local protrusion will change the air pressure distribution because the deformation changes the original ABS. In other words, the FH is sensitive to both the original ABS design and the slider nano-deformation. A new approach has been proposed and investigated to have an optimal design of ABS such that the FH changes are much less sensitive to the nano-deformations. This has been achieved based on numerical evaluations of slider dynamics, and the fact that a high air bearing pressure enhances the heat dissipation and, therefore, reduces the thermal deformation. A dual steps ABS has been proposed. The performance of the dual steps ABS has been evaluated by numerical simulations, and the results show that the flying height with the

dual steps ABS will remain almost unchanged even when a write current as high as 50 mA is applied to the slider. The new slider ABS design can provide higher air bearing pressure and air bearing stiffness without much additional process and extra cost. This design concept has been widely accepted by the industry and has been implemented in some of the hard disk drives nowadays.

Keywords: magnetic data storage, hard disk drive, head-disk-interface, tribology, slider technology, thermal-induced nano-deformation, flying height.

Acknowledgements

It is my pleasure to thank the many people who helped to make this thesis possible.

Firstly, I humbly appreciate my supervisor Prof. Huang Xiaoyang. He became my supervisor when my previous supervisor Prof. Tso Chin Ping retired in 2004. Prof. Huang had to study the knowledge in HDD area so as to give me enough guidance. And in the following 5 years when I joined industry he continuous gave me encourage completing my thesis. That is the main reason I never give up my studentship to achieve the PhD title even after 8 years time.

Next, I am really grateful to the excellent supervision, constructive suggestion and patient encouragement from my co-supervisor, Dr. Liu Bo. Without his help, the completion of this thesis work would not be possible. Most of my research work was done in DSI with Dr. Liu in the first 3 years full-time study, and those 3 years gave me so many pleasant memories and proud achievement. Dr. Liu gave me very details and effective guidance all the way through the 8 years and he always encourage me to conquer the project to build up my capability so as to make contribution to the society. I will keep what he taught me in my whole life.

I would also like to extend my gratitude to Prof. Hu Shengbin, Dr. Ma Yansheng, Dr. Yuan Zhimin, Dr. Zhang Mingsheng, Dr. Yang Mingchu and Dr. Li Jianhua, who have been

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Furthermore, I really appreciated DSI for providing me with their first class working environment and facilities. I would also like to specially thank Nanyang Technological University and the school of Mechanical and Aerospace Engineering for their research scholarship.

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Nomenclature

d	Air-bearing thickness	[m]
F	Air bearing force	[N]
F_g	Gram load	[gram]
G	Temperature of slider	[K]
h	Heat transfer coefficient	[W/m ² ·K]
H	Flying height	[m]
I	Write current	[A]
k	Thermal conductivity of air	[W/m·K]
k_s	Stiffness of air bearing	[N/m]
p	Air bearing pressure	[P]
p_0	Air bearing pressure at atmosphere	[P]
P_r	Prandtl number	
q_{vis}	Viscous dissipation	[W/m ²]
Q	Heat power generated by write current	[W]
R	Resistance of head	[Ohm]
T_s	Slider temperature	[K]
T_d	Disk temperature	[K]
V_s	Volume of heat source	[m ³]

Greek Symbols

α	Coefficient of head resistance to temperature change	[Ohm/K]
γ	Specific heat ratio	
ξ	Mean free path of the air	[m]
λ	Mean free path of the air	[m]
σ_T	Thermal accommodation coefficient	
ω	Temperature exponent of the coefficient of viscosity	

Abbreviations

ABS	Air Bearing Surface
AE	Acoustic Emission
AFM	Atomic force microscope
CML	Computer
DFHT	Dynamic Flying Height Tester
DLC	Diamond Like Carbon
DSI	Data Storage Institute
FFT	Fast Fourier Transform
FH	Flying Height
FHM	Flying Height Modulation
GMR	Giant Magnetoresistive
HDD	Hard Disk Drive
HDI	Head Disk Interface
HGA	Head Gimbal Assembly
HGST	Hitachi Global Storage Technologies
HMS	Head-Media Magnetic Spacing
HSA	Head Stack Assembly
ICP	Inductive Coupling Plasma
LCR	Resistance, inductance and capacitance meter
MR	Magnetoresistive

PTR	Pole Tip Recession
PTP	Pole Tip Protrusion
rpm	Revolution per minute
TDH	Touch-Down Height
TDV	Touch-Down Velocity
TFC	Thermal Flying-height Control
VCM	Voice Coil Motor
WPTP	Write-induced Pole Tip Protrusion

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Chapter 1

Introduction

1.1 Information storage and magnetic hard disk drives

Since its introduction in 1956 by IBM, the magnetic hard disk drives (HDD) have been used as the major data storage device for computer systems. The major advantages of magnetic hard disk drives include their low cost per megabyte, high data transfer rate, and short access time. Over the past decades, the disk driver industry has achieved dramatic progresses in both storage capacity and overall performance. The areal density at the time of this thesis work (2001) was about 20~30 Giga-bit (10^9) per square inch and researchers were pushing technology innovation and development in all aspects to achieve the area density of data storage to 1 Tera-bit (10^{12}) per square inch on a disk.

The increase of the areal density is of great economic and technical interest. IBM introduced the first hard disk, IBM 305 RAMAC, in 1956. RAMAC had an areal density of 2,000 bits/in². Typical hard disk drives in the market in 2005 offer densities between 100 and 150 Gbit/in², an increase of about 75 million times over the RAMAC. With the introduction of perpendicular magnetic recording technology to mass production, Toshiba featured a density of 179 Gbit/in² in 2005. Figure 1.1 shows the areal density growth of the Hitachi Global Storage Technologies (HGST) hard disk drives. It is expected that research and technology breakthrough can lead the areal density to 1

Tera-bit per square inch in 2010~2011 (Wood, 2000).

Figure 1.1. Hitachi Global Storage Technologies advanced storage roadmap (Hitachi, 2003).

1.1.1 Disk drive structure

Figure 1.2 shows a typical top view of magnetic disk drive (top cover removed) and components of a magnetic disk drive. In general, a hard disk drive consists of one or more than one pieces of magnetic disks to store data, a spindle motor to rotate the disks, read/write heads for data recording and retrieval, one actuator to drive the read/write head to the targeted data track and the corresponding sector on the disk.

The read/write heads conduct data recording and retrieval operations. The read/write

head is carried by a device called slider which floats on a cushion of air, aiming to minimize the spacing between head and disk. The flying height of the read/write head is only a few nanometers in modern designs. As a writing head flies over the spinning disks, the head magnetizes the surface in a pattern which represents the data in digital forms.

Each head-slider is held by a triangular-shaped actuator arm (called suspension). The head and arm is controlled by an actuator called voice coil motor (VCM) which is capable of positioning with nanometer resolutions. The arms are then fixed together to form a head stack assembly (HSA). The voice coil motor can therefore position the heads at any targeted track on the disk surface by driving the head stack assembly.

Figure 1.2. Top view of magnetic disk drives (Ultrastar 15K300 3.5 inch Hard Disk Drive from Hitachi Ltd.). VCM stands for

1.1.2 Head disk interface and challenges for ultra low flying height

Head disk interface and flying height

Figure 1.3 illustrates the head disk interface between the slider and rotating disk.

Figure 1.3. Side view of head disk interface

The read/write head is held by a mechanical device called slider. The slider's surface facing the disk is called the air bearing surface (shown in Figure 1.4). The distance between the slider and disk, flying height, is determined by several parameters, including the relative motion speed between slider and disk surfaces, and the gram load from suspension and dynamic flying performance of the slider which is affected by the ABS designs.

The slider is self-pressurized by the airflow associated with the rapidly spinning disk or the high speed relative motion between slider and disk. A very thin and highly compressed air bearing film is generated between the slider and disk surface. The magnetic spacing between the read/write head and the magnetic disk has significant effect on the read/write performance. Reducing the magnetic spacing between the transducer which is housed on the slider and the disk media is important in order to

Figure 1.4. A pico slider air bearing surface (ABS) design.

increase the areal density for data storage. Figure 1.5 is a spacing illustration of the head-disk interface, starting from the surface roughness on the read/write head, then the head overcoat, the head-disk clearance (flying height, FH), down to the disk overcoat and surface roughness on disk magnetic layer. Reducing the magnetic spacing can be achieved by reducing the surface roughness, reducing the thickness of the overcoat and lubricant thickness, or by reducing the flying height.

Figure 1.5. Details of layers between the read/write head on slider and the magnetic layer on disk. DLC: diamond like carbon, FH: flying height.

Figure 1.6 shows the history of area density vs. flying height. It indicates that reducing the slider flying height in hard disk drives is critical for achieving ultra-high recording densities. Currently, giant magnetic recording transducer and longitudinal magnetic media are capable of pushing areal density up to 200 Gbit/in² with a physical spacing between the head (recording slider) and the disk media around 5 nm. Researchers are exploring technology solutions so as to moving the head disk spacing from current level of 7-10 nm to merely 2.5-3.5 nm level or even contact recording. The recent success in the demonstration of 3.5 nm flying height (FH) slider technology (Xu, et al., 2003; Bo, et al., 2004, 2005) has led the researchers to the next flying height target at 2.5 nm or contact recording, aiming to the realization of Tbit/in² areal densities.

Figure 1.6. Slider flying height vs. areal densities on disk.

Challenges for ultra-low head disk spacing

Robust and reliable operation of a modern hard disk drive depends critically on the head-disk interface technology. In fact, more than 90 % of disk drive failures come from head-disk interface problems. Careful designs of the air bearing surface (ABS) and the head disk interface (HDI) are therefore crucial in providing a robust physical spacing between the read/write head and the magnetic disk down to 10 nanometers in today's hard disk drives. This includes how to minimizing the flying height fluctuation caused by various factors which may be less important previously for large flying heights, including thermal-induced slide deformation and nano-protrusion.

1.1.3 Thermal-induced nano-deformation and its effects on head-disk spacing

Heat will be generated in the slider read/write head by the electric current during the process of reading/writing due to Joule losses in the coils, as well as eddy currents and magnetic hysteresis losses in the yoke. Normally, the write current is 0-60 mA and the read current, called read bias current, is 0-5 mA. They all generate heat in the coil and yoke, and the writing-induced heat is much greater than the heat generated by the read current (Wang, et al., 2001; Pust, et al., 2002). The heat associated with the write current will cause temperature rise in the slider, especially around region where the read/write head is located. The local heating not only increases the head temperature, but also creates a thermal gradient. As a result, it will induce deformation in the slider and protrusion of the head elements with respect to the substrate because the mismatch of thermal expansion of various materials used in the read/write head.

The flying height between the read/write head and the disk surface may decrease significantly because of the thermal-induced slider deformation when a write-current applied to the write coil is at an elevated temperature. The previous studies (Gupta, et al., 2001; Wang, et al., 2001; Imamura, et al., 2002; Pust, et al., 2002; Yan, 2002; Liu and Han, 2003; Xu, et al., 2003; Nikitin, et al., 2004; Kurita, et al., 2005) indicated that local heating generated head material protrusion towards the disk and protrusion occupied the spacing between the read/write head and the disk, which dramatically increased the risk of head-disk contact. Such nano-deformation can lead to a flying height drop up to 1

nm. Thus it is important to come up with proper schemes so as to reduce the flying height change associated with thermal-induced slider deformation.

1.2 Objectives

The research work presented in this thesis is a systematical study on the thermal-induced nano-deformation in slider and its effect on the head disk interface. The main objectives are:

1. To quantify thermal-induced slider deformation, local protrusion and the resultant slider flying height changes.
2. To analyze and simulate temperature rise, thermal deformation in slider and the flying height changes.
3. To carry out a study on reducing and controlling thermal-induced slider flying height changes.

It is an attempt to have a better understanding on the write current induced thermal protrusion inside slider and its effects at the slider head –disk interface, and to develop a slider with thermal stability for ultra-low flying height sliders.

1.3 Organization of Dissertation

Chapter 1 provides the background of technology development in hard disk drives and

thermal-induced slider flying height changes. The objectives of the present study are also stated in this chapter.

Chapter 2 presents a literature review of the present research work on hard disk drives and the interface between the slider head and rotating disk, especially the thermal effect in a head disk system by the write current.

Chapter 3 addresses experimental measurements on some parameters associated with thermal effects, including write current induced slider temperature rise, slider crown changes, local protrusions, and flying height changes.

In Chapter 4, analytical solutions for the temperature distribution in the slider are developed, together with numerical simulations on slider's temperature rise, the slider deformation and slider flying height by commercial software ANSYS and CML. This is not only to better understand the thermal effects on sliders, but also to establish a capability in modeling the thermal effects in sliders.

In Chapter 5, dynamic forces and moments on the slider air bearing surface (ABS) are examined and analyzed. A new design of slider ABS is proposed to control the thermal-induced flying height changes. The new ABS is based on a mechanism to increase air pressures around read/write head near the slider trailing edge, which will leads to: (i) lifting the trailing edge to compensate thermal-induced flying height

reduction, (ii) increase the heat dissipation around the trailing edge so that the temperature rise associated with write current will be eased and thermal deformation will be reduced.

Finally, in chapter 6 the conclusions are drawn from this PhD study.

Chapter 2

Literature Review

The literature review in this chapter covers the research work involved in thermal effect in HDDs in three periods: research work published before 2001 or before the start of this PhD thesis, the research work published from 2001 to 2004 when the author was full-time PhD students and thermal issues in HDDs became active research topics; and the research work published from 2005 to 2008 when the author worked in HGST and still closely monitored the research development on thermal effects in HDDs.

2.1 Introduction

The ever-increasing demand of recording areal density has continuously required reducing the spacing between the magnetic recording heads and the disk media. In a hard disk drive (HDD), the spacing between the magnetic recording heads and the disk media is controlled by the height of the slider flying over a rotating disk, called flying height. In 2000, the flying height has been reduced to 10~12 nm for an area density of about 20 Gb/in² (Thompson, 2000; Hikami, 2000; Kryder, 2000; Gangopadhyay, 2000). In order to achieve areal recording densities of 1 Tbit/in², the flying height is required to be further reduced to 3 nm with variations within $\pm 10\%$, that is -0.3 nm ~ 0.3 nm (Menon, 1999; Wood, 2000). With such an ultra-low flying height and

ultra-small flying height variation, the probability of head-disk contact during HDD operation would be very high. Many factors that may be neglected previously with higher flying height must be taken into account in this case. The thermal expansion of the read/write head, which is induced by the ambient temperature or the write (data recording) current, is one of these factors that draw the attention of the researchers in developing high density HDDs.

During the read/write operation in the hard disk drive, both the electric-current-induced Joule heat and the eddy-current-induced Joule heat will be generated, which profoundly increase the slider temperature. The former is generated by the write current in write coils, while the latter is resulted from the self-interaction of the eddy currents induced in all the electrically conducting materials in the slider when an alternating electromagnetic field is imposed. The generated heats are conducted within the slider and exchanged with the adjacent airflow produced by the spinning disk. If the applied current and its frequency are sufficiently high and the heating time is long enough, pronounced temperature gradient appears in the regions near the read/write head, resulting in thermal expansion of this part, called local protrusion.

Such a write current induced thermal protrusion on the slider's air bearing surface alters the airflow between the slider and the disk and the air bearing pressure will be re-distributed over the air bearing surface. Correspondingly, the slider's flying height

will be changed in certain levels. This chapter presents a literature review of temperature rise and thermal protrusion inside slider body. It covers three parts: (1) write current induced temperature rise in slider; (2) thermal-induced protrusion and its effects; (3) air flow's cooling between head/slider and disk surface.

2.2 Write current induced temperature rise

The read/write elements of a magnetic head carried by the slider consist of thin layers of different materials, including write poles, read sensor, shields, undercoat, overcoat, coil, insulation layer, and the substrate. Figure 2.1 shows a schematic of the head structure. The heat generated in write heads causes extra temperature rise in these elements. A number of studies have been reported on the heating in read/write heads.

Figure 2.1. Schematic of a head structure

Klaassen and van Peppen (1999) reported measurements of the temperature rise in a coil and the temperature rise time as a function of write current frequency. They developed an approximate lumped thermal model, but did not report quantitative comparison of their model prediction with the experimental data. Researchers paid more attentions on the write current induced heating problem when the flying height reduced to a low level around 10 nm. Not much attention was paid to the thermal-induced deformation effect in read/write heads before year 2000. Wang et al. (2001) measured the read/write head temperatures as functions of write current, frequency and the slider flying conditions. They used the temperature sensitivity of the magnetoresistive (MR) read/write head to measure temperature changes. The temperature sensitivity of the MR head was calibrated to set up a relationship of head resistance and head temperature. The temperature rise in the write coil for a flying head was found to be much less than a head on the load/unload ramp. The measured temperature coefficient was consistent with the simulation result. Figures 2.2 to 2.4 present some results from Wang et al. (2001), which are temperature rise versus writing power and writing frequency with the read/write head resting on the ramp and flying over a rotating disk respectively.

Figure 2.2. Temperature rises of the coil and the MR sensor due to DC write power with the slider resting on the ramp by Wang (2001).

Figure 2.3. Temperature rise of the coil and the MR sensor due to DC write power with the slider flying on a disk at 10 K RPM by Wang (2001).

Figure 2.4. Normalized increase in head temperature with respect to $F = 0.5$ MHz as a function of write frequency by Wang (2001).

It was not until 2002 that the thermal effect in read/write head became a very active research topic in hard disk drives. The author studied the write current induced flying height change, and the results were published in a conference (Han 2002). Pust et al. (2002) presented a study on thermal-mechanical performance of recording head by using 3-D finite element simulation of the device in operation conditions. Their results showed that the distribution of thermal stress in a read/write head changed completely due to protruded head surface. During head operation, the primary heating source was the writer coil. The maximum temperature and the temperature distribution depended the heat dissipation of the head. As the transducers continued to scale down in size, along with increasing areal density and data read/write rate, the heat needed to be dissipated per unit volume increased due to the larger coil resistance in the core region. The study by Pust et al. (2002), however, neglected heat generation due to eddy current or magnetic hysteresis in the yoke structure, which was important in high-frequency writing operations.

Jang et al. (2002) measured the temperature rise in a giant magnetoresistive (GMR) sensor resulting from heat dissipation in the adjacent write head. One of the key observations was the significant difference in the measured temperature rise with the slider flew over a disk or not. No detailed thermal modeling in his work, however, it was carried out to quantitatively explain this observation.

Imamura et al. (2002) developed an in situ measurement technique to evaluate

temperature distribution over slider air-bearing-surface (ABS) by using infrared thermograph. The ABS temperature distributions were directly measured when the slider was loaded on the disk and a writer current was applied. This measurement system utilized a commercially available spin stand and an infrared thermovision camera system as shown in Figure 2.5. An up-facing head gimbal assembly (HGA) was mounted on the head stage below the rotating disk, which could be loaded on or unloaded off from the disk. The camera was fixed to an X/Y/Z-stage hanging above the disk to observe the ABS below the transparent disk. Figure 2.6 presents the results from this temperature measurement system. The temperature around the read/write head was increased about 10°C when a 0.5MHz and 50mA write current was applied. Imamura's work demonstrated that the write current could induce a significant temperature increase at read/write head.

Figure 2.5. The experimental set up for a dynamic head temperature measurement system (Imamura et al. 2002).

Figure 2.6. Typical images from in situ temperature measurement system. Thermal images of the ABS through a rotating sapphire disk when the slider was loaded at a flying height of 14 nm. (a) When there was no write current applied, uniform temperature was observed throughout the ABS. (b) When a writer current of 50 mA at 0.5 MHz was applied, high temperature was observed only in the vicinity of the head element. Temperature at most of the other parts away from the element on the ABS did not change much(Imamura et al. 2002).

When the experimental results of write current induced flying height change in this project was published in 2002, the write current induced thermal problem became even hot. Some researchers noticed that the flying height decreased significantly because of the thermal expansion of the pole tips, when a write-current was applied to the write head. Optimizing the head structure is thus extremely important for minimizing the head protrusion. To do so, it requires a detailed understanding of the temperature distribution on the air-bearing surface and around the head structure.

Xu (2003, 2004) did a series of study on temperature rise in ABS using in situ temperature measurement technique. The temperature distributions were measured by applying a DC or AC current to the head coil with or without slider flying. An infrared objective lens was used to obtain a high spatial resolution up to 3 μm . The disk was

rotating at 10000 rpm and the flying height of the slider was about 15 nm. Figure 2.7(a) shows the temperatures on the ABS under flying/not-flying conditions and zoomed pictures around the read/write element are given in Figure 2.7(b). It was also found that an eddy current induced by high frequency write-current significantly increased the temperatures on read/write elements, and the point of maximum temperature was changed from the head core to the write gap when the applied current was switched from DC to AC.

Figure 2.7. Line distribution of temperature with a slider flying (10,000 RPM) and a slider not-flying. (a) Line distribution of temperature over whole air-bearing surface and (b) line distribution of temperature around read-write elements by Xu in 2004

The cooling effect produced by the rotating disk was quantified by Xu (2004). As shown in Figure 2.8, the temperature rise at the read/write head would be much slower when the slider was flying over a rotating disk (10000 rpm), comparing to the not-flying situation.

Figure 2.8. Temperature increase as a function of dc write power (Xu 2004).

Sungtaek Ju et al. (2005) conducted experimental and theoretical studies on thermal effect on read/write head. The result showed that the magnetic saturation of yoke structures and the heat transfer across the air bearing strongly influenced the magnitude and spatial distribution of the temperature rise. They conducted three-dimensional numerical simulations to model self-heating in read/write head as a function of the amplitude and frequency of write current pulses.

Song et al. (2007) numerically analyzed the alternating write-current-induced pole tip

protrusion (WPTP) generated in longitudinal magnetic recording (LMR) heads. An integrated magneto-thermal-mechanical model was developed for the simulations of the electromagnetic Joule heating generated in the LMR writer, together with the slider temperature distribution and the slider deformation. The computed results were compared with the experimental measurements in terms of writer resistance and inductance, the WPTP, and temperature rise at reader location. Some results are shown in Figure 2.9. It was seen that as the current frequency increases, the write head resistance linearly increased while the inductance linearly decreases. The inductance is a measure of the magnetic energy stored in the write head. The strong dependence on the write current frequency indicated that the eddy current loss in the yoke dominated over the Joule heat generated in the write coils in that study. The similar situation was also observed in the comparison between the simulation and experiment on temperature rise and WPTP, which were re-plotted in figure 2.10. It showed that the head temperature and WPTP increased when the frequency of write current increased. The heat was mainly generated by the eddy current.

Figure 2.9. Calculated and measured write coil resistance and inductance versus frequency by Song et al. (2007). L: Inductance. R: Resistance

Figure 2.10. Calculated and measured WPTP and temperature rise at reader location versus frequency by Song et al. (2007).

2.3 Thermal-induced protrusion and its effects on head disk interface stability

Write current will generate heat and increase temperature around the read/write head. As a consequence, the read/write head materials will experience thermal expansion, which is called protrusion. The head protrusion is the material protrusion over slider ABS (air-bearing-surface) towards the disk surface. Since the write current in a working disk drive is up to 50 mA while the read current is less than 5 mA, the major heat source in a head is therefore the current in coil of write head (or writer coil), and the protrusion of write pole is thus the most critical and is most close to the write coil.

Gupta et al. (2000) measured write pole tip protrusion (PTP) with temperature rise using an optical profiler and an atomic force microscope (AFM). Figure 2.11 showed the pole tips protruded above the ABS surface by 3-4 nm when the temperature of the head was raised by 50°C. In their work, different head designs with single layer writer coil and dual layer writer coil were measured and simulated. Both results showed that heads with single layer of writer coil exhibited significantly lower thermal PTR than those with dual layers of coils. It explained that the heat was mainly generated by the writer coil, and the smaller resistance of the writer coil was, the less thermal effect would be.

A finite element model was also developed by Gupta et al. (2000) to understand the effect of uniform temperature and write current on different write pole designs. The simulation was conducted by ANSYS software. The ABS profiles at elevated temperature were generated by using the finite element modeling of the thermal expansion of various layers in the head stack, and the results agreed well with the measured profiles. Figure 2.12 presents the simulation result by ANSYS, which was a 2D illustration of the head protrusion in slider height direction. It was proposed by Gupta et al. (2000) that the thermal-induced pole tip protrusion and alumina overcoat protrusion could be reduced by optimizing the thermal expansion coefficient of the alumina basecoat and overcoat, the height of the head stack, and by replacing alumina with SiO_2 and SiC .

Figure 2.11. Representative AFM images over the pole tips regions at (a) ambient temperature and (b) elevated temperature (75°C). The 50°C temperature increase results a protrusion of shields by 3–4 nm (Gupta et al. 2000).

Figure 2.12. Illustration of the distribution of materials in the various layers, the mesh density of the 2D finite element model, and a graphical representation of the ABS surface displacement driven by the uniform temperature change (Gupta et al. 2000).

In Gupta's study, the head protrusion was measured statically by AFM without the cooling effect of disk rotation. Wang et al. (2001) developed a touch-down height measurement method to get the head protrusion towards disk direction when the slider was flying over disk. The head protrusion was studied by using an acoustic emission (AE) sensor which was attached to head gimbal. As the disk velocity decreased the rectified AE rms signal generally decreased initially and increased rapidly when the head made contact with the disk at the touch-down velocity (TDV). The flying height, at which the disk velocity reached TDV, was defined as the touch-down height (TDH). He found that TDH was about 9.5 nm without write current and was increased to about

12.4 nm at write current 40 mA, as shown in Figure 2.13. The increase of TDH was due to the head protrusion induced by write current.

Figure 2.13. AE rms signal during velocity spin down at four different DC write currents. The touch-down height was 9.5 nm at 0 mA (Wang et al. 2001).

Further study for the head protrusion by this touch down method was carried out by Wang et al. (2001), in which AE waveforms were captured for write currents of 30mA, 60mA and 100mA respectively. The results plotted in Figure 2.14 show that AE signal increased when the write current was increased, indicating that large head protrusion induced by large write current would result in stronger head-disk interaction, so as to increase the AE signals.

Figure 2.14. Measurement results by Wang et al. (2001) illustrated that head-disk contact (from AE) was detected at the write currents 60 mA and 100mA, due to thermal-induced protrusions, but not at 30mA.

Yan (2002) reported a 3-D finite element analyses, both steady-state and transient-state, on head write current induced thermal protrusions. It was found that the head reached 90% of its steady-state temperature within 1.2 ms and non-negligible thermal pole tip protrusion took place in a fraction of a millisecond. The pole tip protruded the most at the beginning of writing. As heat conducted toward the overcoat, the trailing edge of the slider protruded more. When the writing was completed, the overcoat cooled off the slowest. For any given disk glide avalanche, the time constants for head-disk contact and separation could readily be obtained from the finite element model.

Xu and Kurita (2005) reported a study on thermal-induced head protrusion. The results showed that a write-current-induced head protrusion caused more deformation of the alumina overcoat in the horizontal direction, and that an ambient-temperature-induced head protrusion caused more deformation around the read-write elements. Figure 2.15 presents their simulation results of protrusion shape induced by write-current and

ambient temperature rise. Figure 2.16 presents their simulation results of the head protrusion caused by different write head designs. Furthermore, their study results clarified that film materials with higher elastic modulus, lower expansion rate, and higher thermal conductivity would reduce the head thermal protrusion.

Figure 2.15. Two kinds of thermal protrusions in the cross-track direction (thin alumina base coat, short pole and shields) by Xu and Kurita (2005).

Figure 2.16. Effect of pole and shields size on two kinds of thermal protrusions (W-TPR: write-induced thermal protrusion, T-TPR: ambient temperature-induced thermal protrusion) by Xu and Kurita (2005).

In order to characterize interactions between the magnetic and mechanical aspects in read/write heads, the thermal-induced protrusion needs to be mapped both spatially and temporally. Nikitin et al. (2004) proposed a variety of novel experimental techniques for characterizing both temperature-induced and write-induced protrusions in the spatial and time domain. Their results suggested that more effort would be needed in reducing Joule heating rather than in reducing eddy current or magnetic hysteresis losses, which appeared to be relatively small.

The effect of the write-current induced pole tip protrusion on head-disk-interface (HDI) interference was also reported by Li (2004). HDI is the key component in HDD, which is consisted of head, disk and the air flow in between of them. Before that, the triple harmonic method (Yuan 2002) was used for drive level head-media magnetic spacing (HMS) measurement. The triple harmonic method used the drive level read back signal change to calculate flying height changes. The read signal was processed through FFT to extract the first and third harmonics. The spectral signal amplitudes of the first and third harmonics were functions of magnetic spacing. Therefore, from the read signal's spectral signal amplitude, magnetic space between head and disk can be calculated. Figure 2.17 shows the results of slider flying height (FH) to HMS correlation, from which the FH can be obtained from HMS with triple harmonic method. The write current induced protrusion was as flying height change in Li's study. Figure 2.18 presents the protrusion measurement results by the write signal. It was found that the write-current-induced pole tip protrusion (WPTP) was a function of head writing

frequency and duration. At high frequency and consecutive multi-wedge writing, the WPTP reached a few nanometers. For a state-of-the-art HDI design with nominal flying height around 10 nm, WPTP can reduce the HDI clearance dramatically, leading to write modulation and altitude failure.

Figure 2.17. Flying height correlation with drive level HMS by triple harmonic method (Li 2004).

Figure 2.18. Write-current-induced pole tip protrusion (WPTP) as a function of write duration and write frequency (Li 2004).

The triple harmonic method was also used by Song (2007) for WPTP measurement. Both DC and AC write currents were applied on the write head to examine their effect of electromagnetic Joule heating. For the DC write current cases, the write current 70.7 mA was applied to the write head, and the coil resistances were calibrated to be the same as the cases for AC writer current at 200MHz, 300MHz, and 400MHz, respectively. The results of WPTP measurement are illustrated in Figure 2.19, showing that the highest protrusions occur near the write pole in the overcoat. It was also found that the AC-induced WPTP was larger than the DC-induced WPTP.

Figure 2.19. Measured WPTP profiles on the ABS for various write currents, DC and AC. For the DC cases, the applied rms current was 70.7 mA and the equivalent coil resistances were 4.5Ω (DC1), 5.5Ω (DC2), and 7Ω (DC3) for the writer resistances at 200MHz, 300MHz, and 400MHz, respectively.

2.4 Air flow cooling between slider and disk

Both the experimental and the theoretical results suggest that the temperature rise of a MR sensor will decrease as the head/disk spacing decreases, due to the heat transfer

through a rotating disk (Tian et al. 1997 and 2002). Experimental results (Tian et al., 2002) showed that when a slider carrying a magnetoresistive (MR) transducer flew over an asperity that disturbed the steady flying condition, the readout signal fluctuated with the fluctuation of the flying height of the slider. They concluded that the air bearing had a cooling effect on the MR transducer, which made a major contribution to the fluctuation of the readout signal. Figures 2.2 and 2.3 in previous section showed that the head temperature rise in the flying condition can be significantly different from that of the static condition (Wang et al., 2001), indicating that the heat transfer processes occur not only inside the head-slider body but also between the head-slider and disk surface.

The details of heat transfer in the head-disk interface are important for predicting the temperature rise on the slider. However, for the simplification, most of the early works on the Joule heat effects caused by writing operation assumed the heat flux throughout a slider's air-bearing-surface (ABS) was constant (Gupta et al., 2001; Yan, 2002; Pust et al., 2002; Xu et al., 2003; Nikitin et al., 2004). In fact, the spacing between ABS and disk surface varied over the ABS, due to the slider flying with a pitch and roll angle. The airflow acted on the different parts of ABS, weak or strong, depending on the spacing between those parts and the disk.

Zhang and Bogoy (1999) solved the N-S and energy equations with discontinuous boundary conditions to obtain the heat transfer between the slider and the

air-bearing-surface. They assumed that the properties of the air remain constant across the air bearing because the temperature variation was not significantly large, so that it could decouple the N-S equation and energy equation then integrated them separately. The results showed that the heat transfer between the slider and air bearing depended on both the heat conduction which transferred heat from the slider to the air bearing, and viscous dissipation which transferred heat from air bearing to the slider. In most cases the heat conduction dominated the heat transfer and therefore the net result was that heat was transferred from the slider to the air bearing. Under this situation the air bearing was regarded as a coolant. But when the temperature difference between the slider and disk is nearly equal or zero, viscous dissipation dominated the heat transfer and heat was transferred into the slider, the air bearing acted as a heater. Since the viscous dissipation is not large, the viscous heating effect was not significant. The simulation results also showed that the heat conduction effect increased with the decrease of the flying height or disk rotation speed, but the viscous dissipation effect decreased with the decrease of the flying height or disk rotation speed.

Chen et al. (2000) applied the heat transfer modeling proposed by Zhang and Bogoy (1999) to study the thermal dependence of MR signal. They found that, at a very small flying height, for certain kinds of sliders, the MR temperature would decrease with increasing flying height. This was caused by a significant air pressure effect on the heat transfer in the air bearing. However, only the Joule heat caused by reading bias current was studied in this modeling work, though it was noticed that the thermal

energy generated by writing operations was more significant (Wang, et al., 2001; Pust, et al., 2002).

Ju (2000) employed the direct simulation Monte Carlo (DSMC) method to investigate heat transfer and viscous heating in microscale Couette flow. When augmented by the slip boundary conditions, the continuum equations were found to predict thermal conductance accurately even in the transition and ballistic flow regime for Couette flows. The viscous heat generation rate, in contrast, was significantly high, predicted by the slip flow theory. Ju (2000) proposed an alternative approach based on kinetic theory and presented a compact analytic expression for the viscous dissipation rate as follows:

$$h = \frac{k}{d + \frac{4\gamma}{\gamma + 1} \frac{1}{Pr} \lambda} \quad (2.1)$$

where k is the thermal conductivity of air, γ is the specific heat ratio, d is air-bearing thickness, $Pr = 0.7$ which is the Prandtl number and λ is the mean free path of the air. Based on the above DSMC heat transfer mode, Ju (2005) carried out a combined experimental study and numerical simulation of self-heating in a thin-film magnetic recording head due to write currents. The results showed that magnetic saturation of the yoke structure was an important factor affecting the magnitude and spatial distribution of temperature rise in the recording head. The heat transfer across the air bearing had a strong influence on the temperature rise in write heads. This was very different from self-heating in magnetoresistive sensors where very efficient heat

spreading within the surrounding magnetic shields greatly reduced the heat transfer to the disk.

Zhou et al. (2008) derived a generalized heat flux expression which considers various molecular models and temperature effect for any type of thin film bearing between the slider and the disk.

$$q(x, y) = -k \frac{T_s(x, y) - T_d}{h(x, y) + 2b\xi(T/T_0)^{\omega+0.5} p_0 \lambda_0 / p(x, y)} + q_{viscous} \quad (2.2)$$

where ξ is a factor to describe a generalized mean free path of the air at atmospheric pressure for various models, ω is the temperature exponent of the coefficient of viscosity, h is the flying height, p is the air bearing pressure, T_s is the slider temperature and T_d is the disk temperature. The physics behind the heat transfer from the slider to the disk was explained. It was found that the generalized mean free path for various models was a crucial parameter in determining the heat transfer across head-disk interface. Other parameters, such as air temperature and temperature exponent of the viscosity coefficient, also had contributions to the heat flux, especially when the hard disk drive operated in a wide range of temperatures. Figure 2.20 and Figure 2.21 showed the effects of the generalized mean free path ξ on heat flux. Figure 2.21 showed that the heat flux over ABS increased significantly when head-disk spacing (flying height) were reduced to be less than 10 nm, while Figure 2.22 showed that the heat flux decreases when the air temperature increased. Both of Figures 2.20 and 2.21 showed that the smaller the generalized mean free path was, the higher heat flux was going to be.

Figure 2.20. The heat flux over ABS vs slider-disk spacing at various ξ . Air temperature $T=288\text{K}$ and temperature exponent of the viscosity coefficient $\omega=0.75$ (Zhou in 2008).

Figure 2.21. The heat flux over ABS vs air temperature at various ξ . The slider-disk spacing $h=1\text{ nm}$ and temperature exponent of the coefficient of viscosity $\omega=0.75$ (Zhou in 2008).

The cooling effects of air flow on the slider's ABS are strongly related to the slider design. Some researchers developed the design principles according to the relationship

between the heat flux and air bearing pressure. The heat transfer between slider and disk surfaces was numerically simulated by Li. et al. (2005), based on an unstructured adaptive triangular mesh method and the Voronoi polygons control volume method. The simulation results showed that the MR temperature depended on the slider flying attitude, the ABS design and the thermal parameters of the slider body materials. Two approaches can effectively increase the dissipation of heat due to the bias current: (1) using high thermal conductivity materials as slider materials and (2) increasing the heat flux rate on the slider ABS. Moreover, they found that the air bearing pressure and heat flux distribution across slider ABS were determined by the ABS design and flying attitude. The cooling effects were enhanced when disk rotating speed was increased.

Juang and Bogy (2007) studied the effects of ABS on thermal actuation by numerical simulations. They defined five measures of merit, including protrusion rate, actuation efficiency, power consumption, pressure peak, and temperature rise of the sensor, to evaluate the performance of thermal actuation. It was found that the effect of the air pressure was more significant than that of the FH on the heat conduction from the slider to the disk. A new ABS design, called “Scorpion III,” which was primarily supported by the high pressures generated at the side rails, instead of supporting by the center pressure peak, was presented and demonstrated an overall performance enhancement, including virtually 100% efficiency with significantly less power consumption.

Liu et al. (2008) proposed ABS design strategies for a thermal FH control (TFC) slider with high actuation efficiency and a low flying height modulation (FHM). The design concept was based on adjusting the FH when the slider was flying by thermal protrusion. The FH was lower down by the thermal protrusion actuator when the head was reading/writing, then the FH was back up to normal when the read/write function was done. Such a design can realize low FH to achieve high recording density and also can avoid head disk interaction when the slider was continuously flying over a rotating disk with ultra-low FH. In Liu's study, heat flux was the main factor to influence the thermal protrusion of actuator, and heat flux was a function of air pressure as stated in equation 2.2. Therefore, in order to have a larger thermal protrusion, the air pressure of the head needs to be designed smaller. Such design method of adjusting heat flux to control the thermal protrusion was used in this project also.

2.5 Thermal flying-height control (TFC)

Active flying height control is a desired approach towards robust low flying height head-disk interface. However, no actual application of such an active flying height control scheme in commercial disk drives until the development of the thermal flying height control mechanism. Meyer (1999) filed a patent of thermal actuating concept by using an external heating circuit in a slider to generate head protrusion and thus lowered down the flying height. The patent was published in 2003. The heater was connected to a control circuit. It was switched on when the head needed to do a read/write operation.

Figure 2.22 presents the concept of this external heater design. Figure 2.23 shows the slider profile without and with heater applied, it indicates the idea clearly that the local protrusion by the heater drives the head closer to the disk surface.

Figure 2.22. External heater set into a slider to adjust flying height in Meyer's patent. No. 60 is the heater, and No. 58 is control circuit.

Figure 2.23. (a) Slider profile before applying external heater (b) Slider profile with local protrusion after heating in Meyer's patent.

A new concept, called thermal flying-height control (TFC) was brought out in 2005. It was to set a controllable heater inside the write head, and this heater generates protrusion to adjust FH.

Juang (2006) did a detail simulation work to study the heater's effect in a head slider. The heater was set in the write coil of write head. When the control current kept generate heating in the heater, a head protrusion was generated continuously. Consequently, the flying height varied, and could be controlled by the power of the heater from a circuit.

Figure 2.24 displays the simulation model of Juang. A heater was put into the write coil. The rest part of slider was a normal Pico slider used in the industry. Table 2.1 is a typical result from Juang's analysis. When a 30 mW heating power was applied on the heater, a 4.2 nm head protrusion was generated. The head protrusion was calculated by finite element method, and the FH change was simulated by CML code accordingly (CML code is an industry standard ABS modeling and evaluation software). The simulation results showed that the FH was reduced from 4.62 to 1.96 nm with the thermal protrusion of 4.2 nm. Juang's study evaluated the feasibility of FH adjustment using a thermal heater, and it gave a magnitude of the FH change range corresponding to the internal heating.

Figure 2.24. Simulation model of thermal flying height control slider in Juang’s study 2006

Table 2.1. Slider flying performance with head protrusion in a TFC slider

	Protrusion (nm)	FH (nm)	Pitch (μrad)	Roll (μrad)	IMF (g)	Max. pressure (atm)
Before protrusion	0	4.62	215	0.7	0.037	16
After protrusion	4.2	1.96	212	0.4	0.065	30

Liu et al. (2008) refined the TFC slider’s efficiency from ABS design optimization. With consideration of the air bearing’s cooling effect and the put-in-heater’s heating effect, a general thermal protrusion and FH adjustment efficiency was studied. In Liu’s study, a series of air bearing structure was examined and eventually a design strategy was proposed, targeting to achieve high heating efficiency for FH adjustment. The study made the thermal heating induced FH adjustment more effective and it made the TFC technique more mature. The TFC technique has now been applied in the latest industry products to achieve ultra-low FH and ultra-high areal density.

2.6 Summary

The author's work and the work by other researchers, both experimental investigations and numerical simulations, confirmed that the write current generates heat in the head-slider and such a heat induces non-negligible slider nano-deformation and protrusion. The maximum nano-deformation can be in the order of nano-meter, which is very crucial to the slider flying stability in nowadays ultra-low FH system when FH is in the sub-5 nm level to for 1 Tbit/in² areal density recording. Exploring a full understanding of the read/write current induced temperature rise, the thermal deformation/protrusion, and its effects on the HDI stability is becoming an urgent task for high density magnetic recording technologies.

However, most of the work published before 2001, when the author started his research, was focused on slider temperature rise and not many results were reported on the slider protrusion profile and no one reported result of experimental measurement of FH change caused by such heating process. The study of FH change is important, not only because it provides information to know the details of HDI degradation due to the thermal protrusion, but also because it obtains important reference data used in new designs of slider's ABS for ultra-low HDI systems. Besides, most of the simulation works before the present project did not pay much attention on the effects of thermal-induced deformation and protrusion on the slider flying stability in ultra-low FH head disk systems. Furthermore, the heat transfer between the slider, the air bearing and the rotating disk has been found to play an important role the

thermal-induced slider deformation and fly height changes. This part needs to be studied further for new ABS designs.

Chapter 3

Experimental Investigations of Thermal Effect on Sliders and Flying Height

3.1 Introduction

When a slider operates in the recoding mode to write data into a disk, the writing current will generate heat leading to temperature rise in the slider head. The temperature increase in the tiny slider head will then induce deformations of the slider head surface close to the rotating disk. As a consequence of the slider head deformation, the flight height of the slider above the disk, which is around 10 nanometers, may change drastically to affect the recording operations. Experimental studies have carried out to examine thermal effect on the slider, including the writing current induced temperature rise, the slider head deformation, and the flying height changes. The purpose is to quantify the thermal effects associated with the writing current, and the data will be used as references in the flying height control.

3.2 Writing current induced temperature rise in slider head

3.2.1 Experimental setup for temperature measurement

The temperature rise in sliders was monitored by measuring the resistance variation of MR sensor in the slider head, which was used as a thermometer due to its thermal property. An experimental platform was built to find out the relationship between the writing current and the temperature rise inside the slider body. Figure 3.1 shows the experimental setup to measure the temperature rise. The HGA was put on a test stage inside an oven, whose temperature could be controlled from the environmental temperature up to 50 °C. The slider with read/write element was electrically connected to a writing current unit and a monitor unit respectively. The writing current control unit can control the writing current value and the writing current frequency. The resistance of the MR sensor was measured by a LCR --- a type of inductance, capacitance and resistance measurement equipment from Agilent Technologies (Agilent Technologies, 2001).

Figure 3.1. Schematic diagram of temperature measurement.

3.2.2 Sliders

The pico sliders were used in the experiments. Figure 3.2 shows photos of these sliders. The sliders were fabricated in the Data Storage Institute (DSI) Singapore with the technical data listed in Table 3.1. The sliders had pitch angle 158 μ rad, roll angle 5.3 μ rad, and skew angle 0°. Figure 3.3 shows the detailed configurations of the sliders HGA, and Figure 3.4 depicts the ABS of the slider. The ABS is one of the most important aspects of a slider in terms of determining the flying performance of the slider. The ABS was formed by photolithography and a dry-etching process which was carried out by reactive ion etching of the inductive coupling plasma (ICP). A diamond-like-carbon (DLC) layer was used to protect the read/write element from corrosion and to improve the tribological performance of the head–disk interface.

Table 3.1. Slider design parameters

Definition	Value
Dimension: Length×Width×Height (mm)	1.25×1×0.3
Crown (nm)	20
Camber (nm)	0
Rail Recess (micron)	0.1
Base Recess (micron)	1.5
Gram Load (gram)	1.5
Disk Speed (rpm)	5400
Flying height (nm)	12

Figure 3.2. Sliders fabricated in DSI Singapore and used in the experiment.

Figure 3.3. (a) Top view of the head-gimbal assembly used for the measurement, (b) section view of the head layout which shows the coil for the write head and electrical connection to the outside of head.

Figure 3.4. The top view of slider air bearing surface. Green color is the top layer, red color is the 2nd layer, and gray color is the recess area.

3.2.3 Temperature measurement approach

The temperature of the slider was measured by using the writing coil and MR sensor on the head as the thermometers whose resistance changes with the temperature. In this way, the temperature inside the slider during its fly on the rotating disk could be obtained. The relationship between the resistance and temperature is

$$R = R_0[1 + \alpha(T - T_0)], \quad (3.1)$$

where R_0 is the resistance at the reference temperature T_0 , α is a coefficient to be calibrated. The calibration was performed by measuring MR resistance as a function of the temperature. Since the MR sensor is very small and very close to the air bearing surface, it is reasonable to assume that the temperature of the reader is the same as that of the external temperature when there is no heating source inside the slider body. The resistance of the MR sensor was measured as the temperature in the oven was gradually increased from 25°C to 50°C. The results are plotted in Fig. 3.5, where a line is fitted based on data from three sliders. It is seen that the coefficient α has a value 0.001 which was used to obtain the temperature rise induced by the writing current.

Figure 3.5. MR resistance sensitivity calibration, showing that $(R/R_0 - 1)$ has linear relationship with $(T - T_0)$.

3.2.4 Temperature measurement results

The temperature rise in the sliders due to the write current was measured, by monitoring the MR resistance, under different testing conditions. A DC current was applied to the coil from 0 to 50 mA, with interval of 10 mA. In the static test, the slider was held about 10 nm above a static disk, and in the rotational test, the slider was flying over a glass disk and an alumina disk, respectively. The results are plotted in Figure 3.6.

(a)

(b)

Figure 3.6. Temperature rise induced in sliders by write current (DC). (a) The slider is on a glass disk, (b) the slider is on an alumina disk.

It is seen that the heat generated by the write current could lead to temperature rise in the slider up to 66-68°C in the static conditions, and 11-16°C in the rotational conditions. In the working condition of a hard disk drive, the write current can be of values up to 30~50 mA, so the operation write current will cause a significant temperature rise inside the slider body. On the other hand, the airflow generated by the rotational disk can provide cooling effect to reduce the temperature rise. In this study, a 5400 rpm rotating speed reduces temperature as much as 52 °C (from 68°C to 16°C for the glass disk), which suggests that a proper design of sliders with increased airflow around heater source could be a possible approach to reduce the effect of Joule heating induced by write current.

3.3 Heating induced nano-deformation in sliders

The experimental results in section 3.2 have showed that there is significant temperature rise inside slider body when write currents are applied to the coil in a slider. Such temperature rise will cause thermal deformations in the slider, especially on slider's ABS, which will change the flying height and influence the flying stability of the slider. The thermal deformation in a slider is normally manifested by the thermal protrusion and crown. In the experiments, the write current induced local protrusion and crown were observed and measured respectively.

3.3.1 Experimental setup for thermal protrusion measurement

The local thermal protrusion is illustrated in Figure 3.7, showing that part of the slider head has protruded towards the rotating disk due to the thermal expansion. In the experiment, the thermal protrusions in sliders were measured by using a 3-D surface profilometer, as shown in Figure 3.8(a). The operation mechanism of the instrument is illustrated in Figure 3.8(b). It is an optical system, in which the sample surface is illuminated with a “white” light source and brought into focus. The light from the source is collimated and divided using a beam splitter. A portion of the beam is directed to the test surface, and a portion to the reference surface. The reflected beams are then re-combined, forming a pattern of light and dark interference “fringes”. The fringe pattern is projected onto a CCD camera and captured by analysis software. At each point, the fringe intensity is strongest at the “coherence plane,” where the optical path difference (OPD) for that point is zero. The surface profilometer provides advanced metrology capabilities and reliable 3-D surface profilers. It reaches superior vertical resolution of 0.1 nm in a single measurement with high stability. The slider was put flatly on the XYZ stage of the profilometer with its air-bearing surface being the test surface. The slider was electrically connected to a DC supplier, which provided a DC current up to 50 mA.

Figure 3.7. An illustration to show the thermal-induced local protrusion at the slider trailing edge, indicated by a portion in red. The FH is reduced from 10nm due to the local protrusion.

Figure 3.8. (a) The 3-D surface profilometer (NewView 600™ Series, ZYGO) used to measure the thermal protrusion in sliders. (b) Optical schematic of interference microscope of the surface profile meter.

3.3.2 Measurement of thermal protrusion

In the experiment, the thermal protrusion at the trailing pad (local protrusion) on the air bearing surface was measured, because the FH was the lowest at this part and effect of the thermal protrusion is the most severe. The thermal protrusion was obtained by comparing the surface profiles with write current and without write current. The surface profile of the trailing pad was first measured when there was no current applied to the coil. Then a DC current was applied to the write coil. In order to attain the fully stable thermal protrusion profile, the surface profile on the top surface of the trailing pad was measured after a few seconds. The net deformation profile of the pad was obtained by subtracting the profile with no DC current from the profile with DC current. Typical results are shown in Figure 3.9.

Figure 3.9. Typical results for the thermal protrusion measurement. (a) Surface profile without write current, the height of point A is 124.4 nm. (b) Surface profile with 50 mA applied to the write coil, the height of point A is 135.7 nm. The difference is the thermal protrusion, which is 11.3 nm in this case.

Figure 3.10 presents the measurement results of the net deformation at the read/write element location on the top surface of the trailing pad. The slider deformation measurement was repeated 3 times for each point, and the error bars in the figure indicate the testing variation for these measurements.

Figure 3.10. Slider local protrusions at different writing currents.

From Fig.3.10, it can be observed that the local protrusion has a linear relationship with the applied write current. By increasing the write current from 10 to 50 mA, the amount of protrusion linearly increases from about 5.7 nm to 11.3 nm. If the slider flying height is 10 nm, the 5.7 nm protrusion at 10 mA would be a 57% change to the flying height, which is totally unacceptable. Although the airflow cooling, when the disk rotates, will reduce the temperature and therefore the amount of the protrusion, it is still a serious matter to affect the slider’s flying height and flying stability, especially the slider is required to fly at several nanometers in order to achieve Terabit areal density magnetic recording.

3.3.3 Measurement of slider body deformation

At slider body level, the crown and camber are two parameters to characterize the slider’s ABS profiles. Crown is a description of slider curvature in its length direction,

and camber is a description of slider curvature in its width direction, as illustrated in Figure 3.11.

Figure 3.11. Schematic illustrations of crown and chamber in a slider.

In Figure 3.11, the upper picture is a general slider profile of the ABS, and the bottom pictures give some examples for different types of crown shape. Generally, the slider's flying is more sensitive to the crown deformation (Han, et al. 2003). So the experimental measurements are focused on the crown thermal deformation at the body level. The slider crown measurement was conducted by using the ZYGO 3-D surface profilometer and applying DC current to the write coil in the slider. The measured crowns at different current values are plotted in Figure 3.12. Slider surface is considered as an arc, the arc chord height is crown. The slider's arc profile can be measured by ZYGO, and the arc chord height can be calculated by its' software which is crown. The crown measurement was conducted 3 times for each write current applied, and the error bars in

the figure indicate the variations for these measurements. The results show that the slider's crown is reduced from 18.65 nm to 16.11 nm when the write current increases from 0 to 50 mA, indicating that the write current leads to a whole slider ABS surface change in addition to the local protrusion. This slider body deformation will significantly affect the aerodynamic force when the slider is flying over the a rotating disk, so as to affect the flying height stability.

Figure 3.12. Crown of the slider versus write current, measured by the ZYGO 3-D profilometer.

3.4 Measurements of thermal deformation induced flying height changes

In the previous sections, the experimental results have shown the thermal deformations, in terms of local protrusions and crowns on the slider's ABS, when the write current is

applied. In these experiments, however, the thermal deformations were obtained under static conditions, i.e., the slider was not flying on a disk. The deformation may be different when the slider is flying over a disk. In this study, the experiments were conducted to study the flying height change due to applied write current under the flying condition.

3.4.1 Experimental setup

The experimental setup for flying height testing with thermal protrusion induced by write current is shown in Figure 3.13, which is a commercial Dynamic Flying Height Tester (DFHT-IV). The light from the mercury arc lamp is directed through the transparent glass disk and onto the slider. The reflected light, containing information about the spacing between slider and glass disk, is received by the photo-detector for flying height measurement and analysis. The equipment was calibrated to a measurement resolution of 0.25 nm (C. W. Struck, 2001).

The slider was electrically connected to a current supplier and could be loaded to a glass disk. The slider used for the experiments was the same as that described in the section 3.2. The glass disks are super smooth disks especially for dynamic flying height test provided by DFHT Company. The RA (roughness average) value for the disk roughness was about 0.5 nm. Lubrication was dipped on the disk surface with thickness

of 1~1.5 nm. Before the flying height measurements were started, the slider was kept flying on the disk for a few seconds in order to smooth the disk asperities. The write current applied to the slider was generated by signal generator, which could provide signals with various voltages and frequencies. The signal was monitored by an oscilloscope that had a resolution of 0.4 % of initial signal, ensuring the accuracy of the write current. The range of the applied writing current was 0-50 mA, which covered the commonly used write current in hard disk drives. An in-house made software panel was used to control the writing current applied to the write coil.

Figure 3.13. The dynamic flying height tester (DFHT-IV) used in the experiment.

3.4.2 Results and discussions

3.4.2.1 Effect of write current

The effect of write current on the flying height was investigated by applying DC current to the slider, and the test was conducted for three different spindle speeds. At the beginning, the flying height without the write current was measured and the results are given in Table 3.2, together with the designed values for three rotational speeds. The data in Table 3.2 show that the slider flying heights are very close to the designed values, indicating that the slider works well in terms of dynamics characteristics. The data in Table 3.2 also confirm that the flying heights increase with the spindle speeds, due to the higher air pressures generated at the ABS (air bearing surface).

Table 3.2. Designed and Tested FH of the slider without write current

rpm	FH (nm)	
	Design	Measurement
4400	10.8	10.9
5400	11.3	11.5
7200	17.2	17.3

Figure 3.14 show the flying heights at various write currents and spindle rotational speeds. It is seen that the flying height decreases almost linearly when the write current increases from 10 to 50 mA. As indicated in Figure 3.14(b), the reduction of flying height varies from 0.47 nm to 0.89 nm, depending on the write current and rotation

speed, which is much more than the allowed FH fluctuation (± 0.5 nm). The effect on flying height could be worse if FH is reduced further below 10nm. The relative changes of flying height are different at higher rotational speeds, indicating that cooling effect may be different for different FH.

Figure 3.14. Effect of write current on slider flying height at three spindle speeds. Figure (a) is the flying height with write current at different rpm, and figure (b) is the flying height change with write current at different rpm.

3.4.2.2 Effect of write frequency

The experimental investigations were conducted to gauge the effects of the write current frequency on the slider's flying height changes. In this case, the write current was fixed at 50 mA and the frequency was varied from 0 MHz to 200 MHz, which covered most of write frequencies used in practical sliders. The results are plotted in Figure 3.15(a), the flying height versus write current frequency, and in Figure 3.15(b), the flying height change versus write current frequency. It is seen that the FH changes more at low frequencies from 0 to 40 MHz, but very little afterwards up to 200 MHz in the test frequency range, indicating that the write frequency may not significantly affect the flying height.

Figure 3.15. Effect of write frequency on slider flying height at three spindle speeds. Figure (a) is the flying height with write current at different rpm, and figure (b) is the flying height change with write frequency at different rpm.

3.4.2.3 Flying height of different ABS designs

It is known that disk rotation will generate strong cooling effects on the slider's ABS, which will directly affect the heating process during the slider flying on the disk. The lower the FH of slider is, the stronger of its' air cooling effect will be. It is therefore of interest to study the thermal-induced flying height change with different sliders of different flying heights. In order to observe the rotation induced cooling effect, three different ABS designs were used to study the flying heights under various write currents. The three sliders are shown in Figure 3.16. The slider A was a product from Sony and had designed a flying height 35 nm; the slider B was a product from Maxtor and had a designed flying height 20 nm; and the slider C was fabricated in DSI and had the flying height 11.3 nm. The difference of the flying height in the three sliders provided different air cooling conditions. The measurement arrangement was similar to that used in the previous section 3.4.2.2 and the disk rotation speed was fixed at 5400 rpm. The results are presented in Figures 3.17.

Commercial Slider A: FH 35 nm Commercial Slider B: FH 20 nm DSI Slider C: FH 11 nm

Figure 3.16. Three sliders used in the heating and cooling effect study.

It is seen that when the write current (DC) varies from 0 to 50 mA, the flying height drops about 1 nm for Slider A, drops about 0.7 nm for Slider B and drops 0.5 nm for Slider C. Therefore, the flying height is generally decreasing when the write current applied for all these 3 different designed sliders. The flying height changes are less for the sliders with lower operational flying height. However, the relative changes are more for the slider with lower flying height. In the test, the maximum changes are 2.85% for slider A, 3.50% for slider B and 4.42% for slider C, respectively.

Figure 3.17. Effect of write current on flying height for three different sliders. The write current used in the experiment was DC and the disk rotation speed was 5400 rpm.

3.5 Experiment accuracy and errors

In this experiment, the temperature was measured by a precision temperature oven. The resolution of the temperature measurement was 0.1°C, and relative accuracy for the temperature measurement was 0.4%. The slider deformation was measured by ZYGO profilometer NewView 600™ Series. The repeatability of this machine was ±0.1%. The slider profile was measured 3 times for each write current; the variation ranges are presented as error bars in Figure 3.10 and Figure 3.12. The flying height variation was measured by dynamic flying height tester DFHT-IV from Phase Metrics, which had a resolution 0.25 nm. The slider used in this experiment had a flying height

of 11.3 nm, so that the error rate from the flying height tester was $\pm 2.2\%$. In all measurements for the temperature, slider deformation and flying height, the tests were repeated for more than 50 times to average off the random error.

3.6 Summary

A systematic experimental measurement has been conducted to investigate thermal effect on sliders. The measurement covers the temperature rise generated by the write current at the slider head, the protrusion and deformation at the slider associated with the temperature rise, and the slider flying height changes due to thermal-induced slider deformations.

The results show that the write current can generate heat and result in a slider temperature increase up to 60~70°C when the disk is not rotating. On the other hand, the air cooling due to disk rotation can significantly reduce the temperature rise if the head is flying over disk surface. This confirms that the heating produced by the write current at the slider head is strong enough to have thermal effect.

The local slider deformation has been studied by measuring the protrusion at the slider trailing pad and the overall deformation has been characterized by the slider crown. The results show that writing operation can lead to up to 10 nm protrusions plus a

slider crown reduction up to 2.5 nm when 50 mA write current is applied to the slider head. It should be pointed out here that the quantitative study on the thermal-induced slider deformation was first reported by the author at that time, though it is well known nowadays.

The slider flying height measurements were conducted on three types of sliders with different ABS designs and operation flying heights. The disks were rotated at the speed 5400 rpm. The results show that the flying height is always reduced when the write current is applied. When the flying height is lower, the flying height drop is less because the air flow's cooling effect is stronger and it eliminates some heating effect of the write current. On the other hand, the relative flying height drop (the percentage of flying height drop) is more severe when the flying height is lower, which indicates that the thermal-induced flying height change can be a severe problem as the slider flying height is getting lower and lower in high capacity hard disk drives.

Chapter 4

Analytical Study and Numerical Simulation of Thermal Effect on Sliders

4.1 Introduction

The experimental results presented in Chapter 3 have demonstrated that the heat generated by write currents indeed results in temperature rise in the sliders, leading to deformation of sliders and further to the slider fly height variations. In order to better understand the thermal effects on the operation and performance of sliders, analytical

Figure 4.1. Flow chart showing the analytical study and numerical simulations on thermal effects.

studies and numerical simulations are conducted and presented in this chapter. As shown in a flow chart by Figure 4.1, firstly, the analytical study on temperature distributions generated by a heat source are carried out, and the results are used as benchmarks to check with the numerical results produced by the software ANSYS. The numerical simulations on temperature rise and corresponding deformation due to write current for a real slider are then conducted by the ANSYS. Finally, thermal-induced slider deformation obtained from ANSYS are input to an industry standard ABS modeling and evaluation software, the CML code developed by the research team in the University of California, Berkeley. The CML code is specially designed for simulation of slider dynamics, including air-bearing pressures and flying heights, so as to calculate thermal-induced slider flying height changes. Moreover, numerical simulation developed in this chapter offers flexibility in evaluating performance of sliders with various designs, which is used in next chapter for control of fly height stability.

4.2 Analytical solution for temperature field corresponding to a point heat source: Green's function

4.2.1 Analytical model and solutions

In this chapter, the studies on the temperature distributions induced by write current are for the steady states, in which the slider temperature has reached to the maximum corresponding to the applied current. The transient temperature rise was examined by Liu et al. (2009), and the results showed that it would take few milliseconds to reach to a

steady state, depending on the cooling conditions. In a typical data writing process, the writing operation could last for hundreds of milliseconds, when the temperature distribution and thermal deformation have been saturated in steady states. Therefore, the steady state temperature distributions are calculated in the present study.

We consider a rectangular block formed a uniform material, representing the slider, and a point heat source with unit strength located at (x_0, y_0, z_0) , representing the write coil. Let a , b , and c be the length, width and height of the solid block. The schematic representation of the model with the coordinate system is illustrated in Figure 4.2.

Figure 4.2. The slider model used for point source analysis.

A temperature field will be induced inside the solid block and the temperature difference between the block and surrounding air is denoted by $G(x, y, z) = T_{\text{slider}} - T_{\text{air}}$. The solution from the point source will be used as the Green's function for a distributed heat source, which is studied later. The governing equation for the function G corresponding to the point source is

$$\frac{\partial^2 G}{\partial x^2} + \frac{\partial^2 G}{\partial y^2} + \frac{\partial^2 G}{\partial z^2} = -\frac{1}{K} \delta(x - x_0) \delta(y - y_0) \delta(z - z_0) \quad (4.1)$$

where the δ function has been used for the point source with unit strength, and K is the heat conductivity of the slider. When the slider flies over the rotating disk, the heat loss from the air-bearing-surface is much greater than that in other five surfaces, due to high convection by the moving air. As such, we assume the convection condition at the ABS side ($z = c$ in this model) and adiabatic conditions at other five sides of the slider. The thermal boundary conditions for the simplified block are therefore

$$\left. \frac{\partial G}{\partial x} \right|_{x=0} = \left. \frac{\partial G}{\partial x} \right|_{x=a} = 0, \quad \left. \frac{\partial G}{\partial y} \right|_{y=0} = \left. \frac{\partial G}{\partial y} \right|_{y=b} = 0, \quad \left. \frac{\partial G}{\partial z} \right|_{z=0} = 0, \quad \left. \frac{\partial G}{\partial z} \right|_{z=c} = -\frac{h}{K} G, \quad (4.2)$$

where h is the thermal convection coefficient. In order to solve the function G from equation (4.1) under boundary conditions (4.2), function G is separated into two parts, i.e. $G = G^A + G^B$ and they satisfy the following equations and boundary conditions respectively.

For G^A :

$$\nabla^2 G^A = -\frac{1}{K} \delta(x - x_0) \delta(y - y_0) \delta(z - z_0) + \frac{1}{abcK} \quad (4.3)$$

$$\left. \frac{\partial G^A}{\partial x} \right|_{x=0} = \left. \frac{\partial G^A}{\partial x} \right|_{x=a} = \left. \frac{\partial G^A}{\partial y} \right|_{y=0} = \left. \frac{\partial G^A}{\partial y} \right|_{y=b} = \left. \frac{\partial G^A}{\partial z} \right|_{z=0} = \left. \frac{\partial G^A}{\partial z} \right|_{z=c} = 0, \quad (4.4)$$

and for G^B :

$$\nabla^2 G^B = -\frac{1}{abc} \cdot \frac{1}{K} \quad (4.5)$$

$$\left. \frac{\partial G^B}{\partial x} \right|_{x=0} = \left. \frac{\partial G^B}{\partial x} \right|_{x=a} = \left. \frac{\partial G^B}{\partial y} \right|_{y=0} = \left. \frac{\partial G^B}{\partial y} \right|_{y=b} = \left. \frac{\partial G^B}{\partial z} \right|_{z=0} = 0, \left. \frac{\partial G^B}{\partial z} \right|_{z=c} = -\frac{h}{K}(G^A + G^B) \quad (4.6)$$

(1) Solution for G^A

Function G^A can be solved based on the equations (4.3) and (4.4). According to homogenous boundary conditions (4.4), function G^A can be expanded by the Fourier cosine series,

$$G^A = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{l=0}^{\infty} G_{mnl}^A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c} \quad (4.7)$$

The right side of equation (4.3) can also be expanded by the same Fourier series

$$\frac{1}{K} \left[\frac{1}{abc} - \delta(x-x_0)\delta(y-y_0)\delta(z-z_0) \right] = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{l=0}^{\infty} D_{mnl} \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c}. \quad (4.8)$$

In equations (4.7) and (4.8), integer m , n and l do not take zero values simultaneously.

By substituting Equation (4.7) and Equation (4.8) into Equation (4.3), we obtain

$$-\left[\left(\frac{m\pi}{a} \right)^2 + \left(\frac{n\pi}{b} \right)^2 + \left(\frac{l\pi}{c} \right)^2 \right] \cdot G_{mnl}^A = D_{mnl}, \text{ or } G_{mnl}^A = \frac{-D_{mnl}}{\lambda_{mnl}^2} \quad (4.9)$$

where $\lambda_{mnl}^2 = \left(\frac{m\pi}{a} \right)^2 + \left(\frac{n\pi}{b} \right)^2 + \left(\frac{l\pi}{c} \right)^2$

$$D_{mnl} = \frac{8}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c}$$

$$D_{0nl} = \frac{4}{abc} \left(-\frac{1}{K} \right) \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c}$$

$$D_{m0l} = \frac{4}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a} \cos \frac{l\pi z_0}{c}$$

$$D_{mn0} = \frac{4}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b}$$

$$D_{m00} = \frac{2}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a}$$

$$D_{0n0} = \frac{2}{abc} \left(-\frac{1}{K} \right) \cos \frac{n\pi y_0}{b}$$

$$D_{00l} = \frac{2}{abc} \left(-\frac{1}{K} \right) \cos \frac{l\pi z_0}{c}$$

$$D_{000} = 0$$

The function G^A is therefore

$$G^A = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{l=0}^{\infty} \frac{-D_{mnl}}{\lambda_{mnl}^2} \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c} \quad (4.10)$$

where m , n and l do not take zero values simultaneously.

(2) Solution for G^B :

G^B can be solved based on equations (4.5) and (4.6)

$$G^B = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} G_{mn}^B(z) \cos \frac{m\pi x}{a} \cos \frac{l\pi y}{b} \quad (4.11)$$

Substituting equation (4.11) into equation (4.5) yields

$$\frac{d^2 G_{mn}^B}{dz^2} - \lambda_{mn}^2 G_{mn}^B = 0, \text{ and } \frac{d^2 G_{00}^B}{dz^2} = -\frac{1}{abc} \left(\frac{1}{K} \right) \quad (4.12)$$

$$\text{where } \lambda_{mn}^2 = \left(\frac{m\pi}{a} \right)^2 + \left(\frac{n\pi}{b} \right)^2 \neq 0.$$

The solution for G_{mn}^B from the ordinary differential equation (4.12) is:

$$G_{mn}^B = C_{mn} e^{\lambda_{mn} z} + E_{mn} e^{-\lambda_{mn} z} \quad (4.13)$$

By applying boundary condition $\left. \frac{\partial G^B}{\partial z} \right|_{z=0} = 0$, it can be derived that $C_{mn} = E_{mn}$ and

$$G_{mn}^B = C_{mn} \cosh(\lambda_{mn} z) \quad (4.14)$$

The solution for G_{00}^B can be obtained from (4.12) by setting $\lambda_{mn} = 0$:

$$G_{00}^B = C_{00} z + E_{00} - \frac{1}{2} \frac{1}{abc} \left(\frac{1}{K} \right) z^2 \quad (4.15)$$

By using the boundary condition $\left. \frac{\partial G_{00}^B}{\partial z} \right|_{z=0} = 0$, one obtains:

$$C_{00} - \frac{1}{abc} \left(\frac{1}{K} \right) z \Big|_{z=0} = 0, \text{ so that } C_{00} = 0, \text{ and}$$

$$G_{00}^B = E_{00} - \frac{1}{2} \frac{1}{abc} \left(\frac{1}{K} \right) z^2 \quad (4.16)$$

Substitution of (4.7) and (4.11) into the boundary condition $\left. \frac{\partial G^B}{\partial z} \right|_{z=c} = -\frac{h}{K} (G^A + G^B)$

gives the following.

For $m = n = 0$,

$$-\frac{1}{ab}\left(\frac{1}{K}\right) = -\frac{h}{K}\left[E_{00} - \frac{1}{2}\frac{c}{ab}\left(\frac{1}{K}\right) + \sum_{l=1}^{\infty} G_{00l}^A (-1)^l\right] \quad (4.17)$$

So that

$$E_{00} = \frac{1}{ab}\frac{1}{h} + \frac{1}{2}\frac{c}{ab}\frac{1}{K} - \sum_{l=1}^{\infty} G_{00l}^A (-1)^l \quad (4.18)$$

and

$$G_{00}^B = \frac{1}{ab}\left(\frac{1}{h} + \frac{c}{2K}\right) - \sum_{l=1}^{\infty} G_{00l}^A (-1)^l - \frac{1}{2}\frac{1}{abc}\left(\frac{1}{K}\right)z^2. \quad (4.19)$$

For $\lambda_{mn} \neq 0$,

$$\lambda_{mn}C_{mn}\sinh(\lambda_{mn}c) = -\frac{h}{K}\left[\sum_{l=0}^{\infty} T_{mnl}^A (-1)^l + C_{mn}\cosh(\lambda_{mn}c)\right] \quad (4.20)$$

so that,

$$C_{mn} = \frac{-\frac{h}{K}\sum_{l=0}^{\infty} G_{mnl}^A (-1)^l}{\lambda_{mn}\sinh(\lambda_{mn}c) + \frac{h}{K}\cosh(\lambda_{mn}c)} \quad (4.21)$$

and

$$G_{mn}^B(z) = \frac{-\frac{h}{K}\sum_{l=0}^{\infty} G_{mnl}^A (-1)^l \cosh(\lambda_{mn}z)}{\lambda_{mn}\sinh(\lambda_{mn}c) + \frac{h}{K}\cosh(\lambda_{mn}c)}. \quad (4.22)$$

Finally, we have

$$G^B(x, y, z) = G_{00}^B(z) + \sum_{m=1}^{\infty} G_{m0}^B(z) \cos \frac{m\pi x}{a} + \sum_{n=1}^{\infty} G_{0n}^B(z) \cos \frac{n\pi y}{b} + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} G_{mn}^B(z) \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \quad (4.23)$$

G^A can be rewritten as:

$$G^A(x, y, z) = \sum_{m=1}^{\infty} G_{m00}^A \cos \frac{m\pi x}{a} + \sum_{n=1}^{\infty} G_{0n0}^A \cos \frac{n\pi y}{b} + \sum_{l=1}^{\infty} G_{00l}^A \cos \frac{l\pi z}{c} + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} G_{mn0}^A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} + \sum_{n=1}^{\infty} \sum_{l=1}^{\infty} G_{0nl}^A \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c} + \sum_{m=1}^{\infty} \sum_{l=1}^{\infty} G_{m0l}^A \cos \frac{m\pi x}{a} \cos \frac{l\pi z}{c} + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{l=1}^{\infty} G_{mnl}^A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c} \quad (4.24)$$

Since both G^A and G^B are dependent on the source location (x_0, y_0, z_0) , we can write the Green's function for the temperature field generated by the point source as

$$G(x, y, z | x_0, y_0, z_0) = G^A(x, y, z) + G^B(x, y, z). \quad (4.25)$$

4.2.2 Some results from the point source

Based on the point source solutions in equations (4.23) – (4.25), the temperature distributions are calculated and viewed for a simple case, in which the point source is placed at the centre of the slider block, i.e., $(a/2, b/2, c/2)$. The calculations were performed by using Matlab. The detailed Matlab programs are listed in Appendix I. In the calculations, the heat transfer coefficient at the air-bearing-surface is set as $h = 15000$ (Zhang, et al., 1999), and the heat conductivity for the slider material K is 20 W/mK. (Kurita, et al., 2005). Figure 4.3 shows that temperature distribution over the

plane at $z = c/2$, cutting through the source, and Figure 4.4 shows the temperature variations along the centerline on the top surface where $h = 1500$. The effect of the heat transfer coefficient at the air-bearing-surface (ABS) is demonstrated by plotting temperature variations along the centerline through the source under different h values. It is seen, from Figure 4.5, that the maximum temperature drastically dropped when h is increased from 1500 to 15000, while further increase in the heat transfer coefficient at ABS above 15000, does not result in significant drop in temperature.

Figure 4.3. Temperature distribution in the cross section $z = c/2$. The point source is located at the centre ($a/2, b/2, c/2$).

Figure 4.4. Temperature distribution along the centerline of the ABS surface ($y=b/2, z=c$). The point source is located at the centre ($a/2, b/2, c/2$), and heat transfer coefficient $h = 1500$.

Figure 4.5. Temperature distributions along the centerline of middle plane ($y=b/2, z=c/2$) for different h values at the ABS surface. The point source is located at the centre ($a/2, b/2, c/2$).

4.3 Analytical solution for temperature field corresponding to a block heat source

4.3.1 Analytical model and solutions

In a real slider, the heat is generated by the write coil which occupies a space, not a point. The write coil can be modeled by a block heat source. The temperature distribution for a block heat source is calculated based on the results of the point heat source model. Here, the relative temperature change in the slider referring to the surrounding air temperature is denoted by T . The simple model for the slider with a block heat source is shown in Figure 4.6. The slider is of length a , width b and height b , and the block heat source occupies a volume V_s at $a_1 \leq x \leq a_2$, $b_1 \leq y \leq b_2$, $c_1 \leq z \leq c_2$, and has total heating power Q . It is assumed that the air-bearing-surface in this case is also at $z = c$, so that the thermal boundary conditions are the same as that used in equation (4.2).

Figure 4.6. Simple model for a slider with a block heat source.

The governing equation for the relative temperature change takes the form:

$$\nabla^2 T = -\frac{Q}{KV_s} f(x, y, z) \quad (4.26)$$

where the source distribution function is

$$f(x, y, z) = \begin{cases} 1, & a_1 \leq x \leq a_2, \quad b_1 \leq y \leq b_2, \quad c_1 \leq z \leq c_2; \\ 0, & \text{otherwise.} \end{cases} \quad (4.27)$$

The temperature field corresponding to the distributed heat source can be obtained by the following integral involving the Green's function:

$$\begin{aligned} T(x, y, z) &= \iiint_{000}^{abc} \frac{Q}{V_s} f(x_0, y_0, z_0) G(x, y, z | x_0, y_0, z_0) dx_0 dy_0 dz_0 = \\ &= \frac{Q}{V_s} \iiint_{000}^{abc} f(x_0, y_0, z_0) G^A(x, y, z | x_0, y_0, z_0) dx_0 dy_0 dz_0 + \\ &\quad + \frac{Q}{V_s} \iiint_{000}^{abc} f(x_0, y_0, z_0) G^B(x, y, z | x_0, y_0, z_0) dx_0 dy_0 dz_0 \end{aligned} \quad (4.28)$$

where the Green's function G has been derived in section 4.2 and given in equation (4.25). The temperature T can be divided into two parts based on two integrals in (4.28),

$$T = T^A + T^B. \quad (4.29)$$

(1) Solution for T^A

T^A can be obtained from the integral associated with G^A ,

$$\begin{aligned}
 T^A &= \int_0^a \int_0^b \int_0^c \frac{Q}{V_s} f(x_0, y_0, z_0) G^A(x, y, z | x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{l=0}^{\infty} T_{mnl}^A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c}
 \end{aligned} \tag{4.30}$$

where

$$\begin{aligned}
 T_{mnl}^A &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c G_{mnl}^A f(x_0, y_0, z_0) dx_0 dy_0 dz_0 = \frac{-Q_{mnl}}{\lambda_{mnl}^2}, \\
 \lambda_{mnl}^2 &= \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{c}\right)^2 \neq 0
 \end{aligned} \tag{4.31}$$

$$\begin{aligned}
 Q_{mnl} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{8}{abc} \left(-\frac{1}{K}\right) \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{8Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{8Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c} dx_0 dy_0 dz_0 \\
 &= -\frac{8Q}{abcKV_s} \left(\frac{a}{m\pi} \sin \frac{m\pi x_0}{a} \Big|_{a_1}^{a_2} \right) \left(\frac{b}{n\pi} \sin \frac{n\pi y_0}{b} \Big|_{b_1}^{b_2} \right) \left(\frac{c}{l\pi} \sin \frac{l\pi z_0}{c} \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{8Q}{mnl\pi^3 KV_s} \left(\sin \frac{m\pi a_2}{a} - \sin \frac{m\pi a_1}{a} \right) \left(\sin \frac{n\pi b_2}{b} - \sin \frac{n\pi b_1}{b} \right) \left(\sin \frac{l\pi c_2}{c} - \sin \frac{l\pi c_1}{c} \right)
 \end{aligned} \tag{4.32}$$

$$\begin{aligned}
 Q_{0nl} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{4}{abc} \left(-\frac{1}{K} \right) \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{n\pi y_0}{b} \cos \frac{l\pi z_0}{c} dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \left(x_0 \Big|_{a_1}^{a_2} \right) \left(\frac{b}{n\pi} \sin \frac{n\pi y_0}{b} \Big|_{b_1}^{b_2} \right) \left(\frac{c}{l\pi} \sin \frac{l\pi z_0}{c} \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{4Q}{anl\pi^2 KV_s} (a_2 - a_1) \left(\sin \frac{n\pi b_2}{b} - \sin \frac{n\pi b_1}{b} \right) \left(\sin \frac{l\pi c_2}{c} - \sin \frac{l\pi c_1}{c} \right)
 \end{aligned} \tag{4.33}$$

$$\begin{aligned}
 Q_{m0l} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{4}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a} \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{m\pi x_0}{a} \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{m\pi x_0}{a} \cos \frac{l\pi z_0}{c} dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \left(\frac{a}{m\pi} \sin \frac{m\pi x_0}{a} \Big|_{a_1}^{a_2} \right) \left(y_0 \Big|_{b_1}^{b_2} \right) \left(\frac{c}{l\pi} \sin \frac{l\pi z_0}{c} \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{4Q}{bml\pi^2 KV_s} \left(\sin \frac{m\pi a_2}{a} - \sin \frac{m\pi a_1}{a} \right) (b_2 - b_1) \left(\sin \frac{l\pi c_2}{c} - \sin \frac{l\pi c_1}{c} \right)
 \end{aligned} \tag{4.34}$$

$$\begin{aligned}
 Q_{mn0} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{4}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{m\pi x_0}{a} \cos \frac{n\pi y_0}{b} dx_0 dy_0 dz_0 \\
 &= -\frac{4Q}{abcKV_s} \left(\frac{a}{m\pi} \sin \frac{m\pi x_0}{a} \Big|_{a_1}^{a_2} \right) \left(\frac{b}{n\pi} \sin \frac{n\pi y_0}{b} \Big|_{b_1}^{b_2} \right) \left(z_0 \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{4Q}{cmn\pi^2 KV_s} \left(\sin \frac{m\pi a_2}{a} - \sin \frac{m\pi a_1}{a} \right) \left(\sin \frac{n\pi b_2}{b} - \sin \frac{n\pi b_1}{b} \right) (c_2 - c_1)
 \end{aligned} \tag{4.35}$$

$$\begin{aligned}
 Q_{m00} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{2}{abc} \left(-\frac{1}{K} \right) \cos \frac{m\pi x_0}{a} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{m\pi x_0}{a} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{m\pi x_0}{a} dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \left(\frac{a}{m\pi} \sin \frac{m\pi x_0}{a} \Big|_{a_1}^{a_2} \right) \left(y_0 \Big|_{b_1}^{b_2} \right) \left(z_0 \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{2Q}{bcm\pi KV_s} \left(\sin \frac{m\pi a_2}{a} - \sin \frac{m\pi a_1}{a} \right) (b_2 - b_1) (c_2 - c_1)
 \end{aligned} \tag{4.36}$$

$$\begin{aligned}
 Q_{0n0} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{2}{abc} \left(-\frac{1}{K} \right) \cos \frac{n\pi y_0}{b} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{n\pi y_0}{b} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{n\pi y_0}{b} dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \left(x_0 \Big|_{a_1}^{a_2} \right) \left(\frac{b}{n\pi} \sin \frac{n\pi y_0}{b} \Big|_{b_1}^{b_2} \right) \left(z_0 \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{2Q}{acn\pi KV_s} (a_2 - a_1) \left(\sin \frac{n\pi b_2}{b} - \sin \frac{n\pi b_1}{b} \right) (c_2 - c_1)
 \end{aligned} \tag{4.37}$$

$$\begin{aligned}
 Q_{00l} &= \frac{Q}{V_s} \int_0^a \int_0^b \int_0^c \frac{2}{abc} \left(-\frac{1}{K} \right) \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \int_0^a \int_0^b \int_0^c \cos \frac{l\pi z_0}{c} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \int_{a_1}^{a_2} \int_{b_1}^{b_2} \int_{c_1}^{c_2} \cos \frac{l\pi z_0}{c} dx_0 dy_0 dz_0 \\
 &= -\frac{2Q}{abcKV_s} \left(x_0 \Big|_{a_1}^{a_2} \right) \left(y_0 \Big|_{b_1}^{b_2} \right) \left(\frac{c}{l\pi} \sin \frac{l\pi z_0}{c} \Big|_{c_1}^{c_2} \right) \\
 &= -\frac{2Q}{abl\pi KV_s} (a_2 - a_1) (b_2 - b_1) \left(\sin \frac{l\pi c_2}{c} - \sin \frac{l\pi c_1}{c} \right)
 \end{aligned} \tag{4.38}$$

By substituting Q_{mnl} into $T_{mnl}^A = \frac{-Q_{mnl}}{\lambda_{mnl}^2}$, T^A can be obtained as

$$\begin{aligned}
 T^A = & \sum_{m=1}^{\infty} T_{m00}^A \cos \frac{m\pi x}{a} + \sum_{n=1}^{\infty} T_{0n0}^A \cos \frac{n\pi y}{b} + \sum_{l=1}^{\infty} T_{00l}^A \cos \frac{l\pi z}{c} + \\
 & \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} T_{mn0}^A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} + \sum_{n=1}^{\infty} \sum_{l=1}^{\infty} T_{0nl}^A \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c} + \\
 & \sum_{m=1}^{\infty} \sum_{l=1}^{\infty} T_{m0l}^A \cos \frac{m\pi x}{a} \cos \frac{l\pi z}{c} + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sum_{l=1}^{\infty} T_{mnl}^A \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b} \cos \frac{l\pi z}{c}
 \end{aligned} \tag{4.39}$$

(2) Solution for T^B

T^B can be obtained from the integral of the point heat source:

$$\begin{aligned}
 T^B = & \iiint_{0 \leq x \leq a, 0 \leq y \leq b, 0 \leq z \leq c} \frac{Q}{V_s} f(x_0, y_0, z_0) G^B(x, y, z | x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 = & T_{00}^B + \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} T_{mn}^B \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b}, \quad (m \neq n = 0).
 \end{aligned} \tag{4.40}$$

In equation (4.40),

$$\begin{aligned}
 T_{00}^B(z) &= \frac{Q}{V_s} \iiint_{000}^{abc} G_{00l}^B f(x_0, y_0, z_0) dx_0 dy_0 dz_0 = \frac{Q}{V_s} \iiint_{000}^{abc} \frac{1}{ab} \left(\frac{1}{h} + \frac{c}{2K} \right) f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &- \frac{Q}{V_s} \iiint_{000}^{abc} \sum_{l=1}^{\infty} G_{00l}^A (-1)^l f(x_0, y_0, z_0) dx_0 dy_0 dz_0 - \frac{Q}{V_s} \iiint_{000}^{abc} \frac{1}{2} \frac{1}{abc} \left(\frac{1}{K} \right) z^2 f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= \frac{Q}{V_s} \frac{1}{ab} \left(\frac{1}{h} + \frac{c}{2K} \right) \iiint_{000}^{abc} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 - \frac{Q}{V_s} \sum_{l=1}^{\infty} (-1)^l \iiint_{000}^{abc} G_{00l}^A f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &- \frac{Q}{V_s} \frac{1}{2} \frac{1}{abc} \left(\frac{1}{K} \right) z^2 \iiint_{000}^{abc} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= \frac{Q}{ab} \left(\frac{1}{h} + \frac{c}{2K} \right) - \frac{Qz^2}{2abcK} - \frac{Q}{V_s} \sum_{l=1}^{\infty} (-1)^l \iiint_{000}^{abc} G_{00l}^A f(x_0, y_0, z_0) dx_0 dy_0 dz_0 \\
 &= \frac{Q}{ab} \left(\frac{1}{h} + \frac{c}{2K} \right) - \frac{Qz^2}{2abcK} - \sum_{l=1}^{\infty} (-1)^l T_{00l}^A
 \end{aligned} \tag{4.41}$$

$$\begin{aligned}
 T_{mn}^B(z) &= \frac{Q}{V_s} \iiint_{000}^{abc} G_{mn}^B(z) f(x_0, y_0, z_0) dx_0 dy_0 dz_0 = \\
 &= \frac{Q}{V_s} \iiint_{000}^{abc} \frac{-\frac{h}{K} \sum_{l=0}^{\infty} G_{mnl}^A (-1)^l \cosh(\lambda_{mn} z)}{\lambda_{mn} \sinh(\lambda_{mn} c) + \frac{h}{K} \cosh(\lambda_{mn} c)} f(x_0, y_0, z_0) dx_0 dy_0 dz_0 = \\
 &= -\frac{Qh}{V_s K} \frac{\cosh(\lambda_{mn} z)}{\lambda_{mn} \sinh(\lambda_{mn} c) + \frac{h}{K} \cosh(\lambda_{mn} c)} \iiint_{000}^{abc} \sum_{l=0}^{\infty} G_{mnl}^A (-1)^l f(x_0, y_0, z_0) dx_0 dy_0 dz_0 = \\
 &= -\frac{Qh}{V_s K} \frac{\cosh(\lambda_{mn} z)}{\lambda_{mn} \sinh(\lambda_{mn} c) + \frac{h}{K} \cosh(\lambda_{mn} c)} \sum_{l=0}^{\infty} (-1)^l \iiint_{000}^{abc} G_{mnl}^A f(x_0, y_0, z_0) dx_0 dy_0 dz_0 = \\
 &= -\frac{h}{K} \frac{\cosh(\lambda_{mn} z)}{\lambda_{mn} \sinh(\lambda_{mn} c) + \frac{h}{K} \cosh(\lambda_{mn} c)} \sum_{l=0}^{\infty} (-1)^l T_{mnl}^A
 \end{aligned} \tag{4.42}$$

T_{00l}^A in equation (4.41) and T_{mnl}^A in equation (4.42) are obtained from equations (4.31) – (4.38), and λ_{mn} is given in equation (4.12).

4.3.2 Some results from the block heat source

Based on the block source solutions in equations (4.29) – (4.42), the temperature distributions are calculated and viewed for a typical case, in which the block source is placed at the edge formed by the planes $x = 0$ and $z = c$, as shown in Figure 4.6. In the calculation, following parameters and dimensions are set for the slider and heat source.

$$a=1.25\text{mm}, b=1\text{mm}, c=0.3\text{mm}$$

$$a_1=0, a_2=0.01a, b_1=0.45b, b_2=0.55b, c_1=0.67c, c_2=c$$

$$a_2-a_1=0.0125\text{ mm}, b_2-b_1=0.1\text{mm}, c_2-c_1=0.1\text{m m}$$

$$Q = I^2 R, \text{ the write current } I = 50\text{mA}, \text{ and coil resistance } R = 50\Omega$$

So that,

$$\frac{Q}{V_s} = \frac{I^2 R}{(a_2 - a_1)(b_2 - b_1)(c_2 - c_1)} = 1 \times 10^{12} \text{ W / m}^3 \quad (4.43)$$

The calculations were performed by using Matlab. The detailed Matlab programs are listed in Appendix II. In the calculations, the heat transfer coefficient at the air-bearing-surface is set as $h = 15000$ (Zhang, *et al.*, 1999), and the heat conductivity K for the slider material is 20 W/mK . (Kurita, *et al.*, 2005). The temperature distributions are plotted in Figure 4.7 for the front surface ($x = 0$), in Figure 4.8 for the rear surface ($x = a$), in Figure 4.9(a) for the top surface (ABS), and in Figure 4.9(b) for the bottom surface. The temperature variations along the centerline on the top surface are specially

plotted out in Figure 4.10. These temperature distributions obtained from the analytical study based on a simplified model will be used later to compare with the results generated by numerical simulations.

Figure 4.7. Temperature distributions on the left side ($x = 0$) surface of the slider with the block heat source located at the edge $x = 0$ and $z = c$.

Figure 4.8. Temperature distributions on the right side ($x = a$) surface of the slider with the block heat source located at the edge $x = 0$ and $z = c$.

Figure 4.9. (a) Temperature distributions on the top ($z = c$) surface of the slider, and (b) temperature distributions on the bottom surface ($z = 0$), with the block heat source located at the edge $x = 0$ and $z = c$.

Figure 4.10. Temperature distributions along the centerline ($y = b/2$, $z = c$) on the top surface (ABS) of the slider.

4.4 Numerical simulation of temperature field in a simplified slider with a block heat source by ANSYS

4.4.1 Numerical model and solution method

The temperature field calculated in section 4.3 for a simplified slider model with a block heat source is simulated in this section by the numerical software ANSYS (version 11.0), and the results are compared with that obtained from analytical methods. In order to facilitate comparison, the model geometry, the loadings, and the modeling parameters used for the current numerical simulation by ANSYS are specified to be the same as those used for analytical analyses. As shown in Figure 4.6, the block source is placed at

the edge formed by the planes $x = 0$ and $z = c$, and the heat source occupies the volume $a_1 \leq x \leq a_2$, $b_1 \leq y \leq b_2$, $c_1 \leq z \leq c_2$. In the calculation, following parameters and dimensions are set for the slider and heat source.

$$a = 1.25 \text{ mm}, b = 1 \text{ mm}, c = 0.3 \text{ mm}$$

$$a_1 = 0, a_2 = 0.01a, b_1 = 0.45b, b_2 = 0.55b, c_1 = 0.67c, c_2 = c$$

$$a_2 - a_1 = 0.0125 \text{ mm}, b_2 - b_1 = 0.1 \text{ mm}, c_2 - c_1 = 0.1 \text{ mm}$$

The heat source strength (power per unit volume) is set to be

$$\frac{Q}{V_S} = \frac{I^2 \cdot R}{(a_2 - a_1)(b_2 - b_1)(c_2 - c_1)} = 1 \times 10^{12} \text{ W/m}^3$$

In the numerical simulations, the heat transfer coefficient at the air-bearing-surface is set as $h = 15000 \text{ W/m}^2\text{K}$ (Zhang, *et al.*, 1999), and to be zero in other surfaces. The heat averaged conductivity K of the slider material is 20 W/mK . (Kurita, *et al.*, 2005).

The mesh generation used in the present simulation is free mesh provided by ANSYS. The effect of different mesh density on accuracy of the numerical results is investigated by calculating the maximum temperature changes on the air-bearing-surface. The results, listed in Table 4.1, show that the free mesh generation gives an acceptable result, as comparing to other mesh sizes and numbers. The meshes generated for the slider model are plotted in Figure 4.11.

Table 4.1. Maximum temperature changes on a-r-bearing-surface calculated with various mesh numbers and sizes.

Mesh grid size	Mesh number	Max temperature (K) changes on ABS
15 μm	127160	51.04
20 μm	52224	50.85
25 μm	27716	51.21
30 μm	18480	51.05
50 μm	3969	51.73
75 μm	1710	50.09
100 μm	660	40.64
Free mesh	20280	50.41

Figure 4.11. Mesh topology for the slider model by free mesh method in ANSYS.

4.4.2 Numerical results and comparisons with analytical modeling

The temperature mappings are plotted in Figure 4.12 for the top air-bearing-surface, and in Figure 4.13 for the left surface ($x = 0$). The comparisons between the ANSYS simulation results and analytical results show that they agree well qualitatively.

Figure 4.12. Temperature distribution on top surface (ABS) of the slider.
(a) Numerical simulation by ANSYS, (b) Analytical calculations.

Detailed comparisons are made by plotting the temperatures along the centerline on the top surface and the edge formed by $x=0$ plane and $z=c$ plane. These are plotted in Figures 4.14. A generally good agreement has been observed, especially the maximum temperatures around the heat source.

Figure 4.13. Temperature distribution on the left surface ($x = 0$) of the slider by ANSYS simulation and analytical modeling respectively.

Figure 4.14. Comparison of temperature distribution along the centerline in top surface ($z = c$) of the slider between ANSYS simulation and analytical modeling.

4.5 Numerical simulation of thermally induced slider deformation and fly height changes

In this section, the numerical simulations are carried out on a real slider to calculate the write current induced temperature changes, the corresponding deformation and the resulted fly height variations. The software used in this study are ANSYS and CML code. As mentioned before, the CML code is the only industry standard software developed by the research team in the University of California, Berkeley, to simulate and evaluate the static and dynamic performance of slider designs for hard disk drive application. The CML code can calculate the key performance parameters of a slider design, including slider’s flying attitudes, fly height, pitch and roll angles of slider, and the air pressure distributions on the air-bearing-surface of the slider.

4.5.1 Numerical model and method

Slider model

A Pico slider with length 1.25mm, width 1mm and thickness 0.3mm is studied. The whole slider is plotted in Figure 4.15(a) with some detailed inner structures, such as the write coil [Figure 4.15(c)]. Since the slider structure is symmetric along a central line, the simulations are carried out over half of the slider to reduce the calculation time and total mesh numbers, which is also shown in Figure 4.15(b).

Figure 4.15. (a) Whole model of the slider, (b) half of the slider under the simulation, (c) writer coil structure.

Meshes

The meshes of slider are generated by ANSYS based on the free mesh scheme. The side view of the meshes is shown in Figure 4.16. And the meshes over the ABS are generated by CML code and illustrated in Figure 4.17(a), together with the actual ABS layout in Figure 4.17(b).

Figure 4.16. Side view of the meshes generated for the slider.

Figure 4.17. (a) Meshes over the air-bearing-surface (ABS), and (b) ABS layout.

Material Properties

The slider is made of several different materials with different thermal and mechanical properties. The material properties used in the simulation are listed in Table 4.2, according to the published date (Lee, et al., 1995, Kurita, et al., 2005).

Table 4.2. Thermal and mechanical properties of slider materials.

Materials	Thermal conductivity (W/mK)	Young's modulus (GPa)	Poisson's ratio	Coefficient of thermal expansion × e-6 /K
Al ₂ O ₃ TiC	20	390	0.22	7.1
Al ₂ O ₃	1.8	138	0.25	7.1
NiFe (pole, shield)	35	200	0.3	12.8
Cu (write coil)	403	130	0.34	15.4

Heat source (write coil)

The write coil generates heat and is therefore the heat source in the simulation. The write coil is made of Cu and its complicated structure is simplified into a uniform piece shown in Figure 4.18. It is an elliptical plate with thickness 0.01mm. The center of the plate is at a point 0.1mm from ABS surface and 0.02mm from the trailing edge of the slider. The write coil is of electrical resistance 50 ohms, based on a direct measurement. The strength of the heat source calculated based on the following equation,

$$\frac{Q}{V_s} = \frac{I^2 R}{\text{source volume}}, \tag{4.44}$$

where I is the write current, R is the electric resistance of write coil. The heat strength is assumed to be uniform over the entire source block.

Figure 4.18. A uniform elliptical plate is used in the simulation as the heat source for the for the write coil.

Thermal conditions at slider surfaces

Bogy et. al. conducted research on the heat transfer coefficient h over surfaces of sliders, and they suggested that, at rotation speed 5400 rpm and flying height 10nm ~ 30nm, the average h value on the ABS surface was approximately 15000 W/m²k, and on the rest of the surfaces was about 70 W/m²k (Zhang and Bogy, 1999). They are listed in Table 4.3. Since the simulations are conducted on half of the slider due to the symmetric configuration, the heat transfer coefficient along the cutting surface is set to be $h = 0$ in the simulation, which is also listed in Table 4.3. When the slider is in stationary state without rotation, the heat transfer coefficients are set to be 70 W/m²k for all slider surfaces, as shown in Table 4.3.

Table 4.3. Heat transfer coefficient h on slider surfaces

	h (W/m ² k), 5400 rpm	h (W/m ² k), stationary
ABS	15000	70
Other slider surfaces (except ABS and cutting surface)	70	70
Cutting surface	0	0

When slider is flying over the high-speeding rotating disk, the airflow will cool the slider in some degree, especially over the air-bearing-surface (ABS). In the ultra-low FH head-disk systems, the depths of slider’s ABS steps and cavity become comparable to slider’s minimal FH. Furthermore, the height of each step can be quite different; therefore, the airflow cooling effects are very different point by point on the surface.

The heat flux can be calculated locally on ABS by the following equation (Li, et al. 2005)

$$q = \frac{k}{H + 2b\lambda_0 P_0 / P} * \Delta T - q_{vis}, \quad (4.45)$$

where ΔT is the temperature difference between the ABS and air bearing, k is thermal conductivity of air, P is the air bearing pressure, H is flying height, λ_0 is the mean-free path of air under atmosphere pressure P_0 , q_{vis} is the viscous dissipation which is negligible in this simulation (Zhang & Bogoy, 1999). b is a constant which is calculated from the following equation (Juang & Bogoy, 2007),

$$b = \frac{2(2 - \sigma_T)\gamma}{\sigma_T(\gamma + 1)P_r} \quad (4.46)$$

where, for air at $T=300K$ and atmospheric pressure, the Prandtl number $Pr=0.7$, the specific heat ratio γ is 1.4, the thermal accommodation coefficient σ_T is 0.9. In equation (4.45), the mean free path $\lambda_0 = 65nm$ and thermal conductivity of air $k = 0.0263 W/mK$.

In the simulations, the detailed heat flux q , over the ABS is calculated based on Equation (4.45), in which the air pressures over ABS are obtained from the CML code.

Numerical procedure

The simulations are based on software ANSYS and CML code. The commercial software ANSYS is used to build a detail model which is much closer to the real slider used in experiment. This software calculates and gives the whole slider temperature distribution profile and slider protrusion (thermal deformation) profile. The ABS protrusion profile from ANSYS is used as an input data in the FH simulation by CML code. The CML code is a dynamic FH simulator to calculate FH with different ABS designs. The FH changes can thus be calculated based the thermal deformation induced by write current in the slider. Since the heat transfer coefficient on the slider ABS needs to be calculated by equation (4.45), which requires dynamic air pressure distributions on ABS, the CML code is also employed at the beginning to generate air pressures on ABS in order to simulate the temperature distributions in the slider.

Figure 4.19. Flowchart showing the numerical simulation procedures for thermal induced slider deformation and flying height changes.

4.5.2 Simulation Results

Heat flux distribution on air-bearing-surface (ABS)

The detailed configuration of the slider's ABS is shown in Figure 4.20 in micro meter scales. The slider read/write element is in a trailing pad of the slider, which is the most closest to the disk. The air pressure distribution plotted in Figure 4.21 depicts that the air pressure is much higher around the read/write element than other locations. As indicated in equation (4.45), the local air pressure will affect the heat flux, thus the heat transfer coefficient. This is shown in Figure 4.22, in which the heat flux around the trailing pad is much greater than elsewhere on the air-bearing-surface. The maximum value is found to be $2.13 \times 10^6 \text{ W/m}^2\text{K}$ When the slider flies, the trailing end (pad) is the closest to the disk surface.

Figure 4.20. The geometry of slider's air-bearing-surface.

Figure 4.21. Simulation results of air pressure distributions on ABS. The slider is flying on a disk rotating at 5400 RPM

Figure 4.22. simulation results of heat transfer coefficient distribution on ABS. The slider is flying on a disk rotating at 5400 rpm.

Temperature distribution and thermal-induced protrusion

The heat flux distribution generated by the CML code, as shown in Figure 4.22, was input into the thermal-structure FE analysis in ANSYS as part of the thermal boundary conditions for the temperature simulations. The temperature distribution and thermal protrusion of the slider were then obtained by using ANSYS structural-thermal solver. The temperature rises are calculated in the simulation results, taking the room temperature 25°C (298K) as the reference temperature.

Figures 4.23(a) and (b) show the temperature distributions inside the slider body by applying DC write currents 20mA and 50 mA, respectively. It can be observed that the maximum temperature rise happens around the write/read element, and the maximum temperature rises are 5.8 K under the current 20mA and 14.4 K 50mA current.

The maximum temperature rises around write/read area are compared with the measured values presented in Chapter 3 of this thesis, and the comparison results are plotted in Figure 4.24 for various write DC currents. The agreements between the simulation results and measured data are generally good at weak write currents, and the difference between them become large at when the write current are above 40mA.

In our numerical simulations, the heat transfer coefficients on the air-bearing-surface are

calculated point by point based on equation (4.45). However, the average heat transfer coefficient can be estimated to be 15,000 (W/m²k), which has been used for the analytical study on temperature rise in the slider. The temperatures along the centre line on ABS obtained from two types of thermal boundary conditions are compared in Figure 4.25. It is seen that the calculated temperature rises based on two types of boundary conditions agree very well.

Figure 4.23. Typical results showing the temperature distributions inside the slider, (a) write current is DC 20 mA and (b) write current is DC 50 mA. The slider flies over a disk rotating at 5400 RPM.

Figure 4.24. Comparison between numerical simulation results and measured values for the temperature rise at the write/read element of slider induced by different write currents.

Figure 4.25. temperature rise along the centre line on air-bearing-surface calculated based on two thermal boundary conditions on ABS. One is to use average value $h = 15000\text{ (W/m}^2\text{k)}$, and the other is calculated heat flux and heat transfer coefficients from equation (4.45). The write current is DC 50mA.

The thermal deformations of the slider are also calculated by ANSYS based on the temperature distributions under various write current. The local protrusion is defined as the surface level increase on ABS comparing to the original level when the slider's temperature is uniformly at the room temperature. The protrusion profiles are plotted along the central line on the ABS, as shown in Figure 4.26, starting from the slider's trailing edge where the write/read element is located.

Figure 4.26. Schematic drawing of slider's air-bearing-surface (ABS).

The local protrusions calculated by ANSYS for the slider flying over a disk rotating at 5400 rpm are plotted in Figure 4.27 with different write currents. The maximum protrusions occur around the area where the write/read element is located, which is called “write pole tip protrusion” or WPTP. Since the local protrusions were measured in the experiment for sliders at stationary disk conditions (the results are presented in Chapter 3), the simulations are also carried for protrusions in the static condition without disk rotation. In this case, the heat transfer coefficient on ABS is set to be $h = 70 \text{ W/m}^2\text{k}$, the same as other external surfaces. The results in this case are plotted in figure 4.28. It is seen that the protrusions in this case are much larger without air cooling on ABS, comparing with that shown in Figure 4.27 for the rotating disk.

Figure 4.27. ANSYS simulation results for local protrusion along the central line on ABS. The slider is on a disk rotating at 5400 rpm. The heat transfer coefficient is set at $h = 15000 \text{ W/m}^2\text{k}$ on ABS.

Figure 4.28. ANSYS simulation results for local protrusion along the central line on ABS. The slider is on a stationary disk without rotation. The heat transfer coefficient is set at $h = 70 \text{ W/m}^2\text{k}$ on ABS.

The local protrusions simulated by ANSYS are compared with the experimental data for stationary cases. The comparison results are plotted in Figure 4.29 for the maximum protrusions around write/read element area at different write current. It is seen that simulation results on the maximum protrusions agree well with the experimental values.

Figure 4.29. Comparison of ANSYS simulations results on maximum protrusions with the measured values for stationary cases without disk rotation. The simulated results for rotating disk at 5400 rpm are also shown in the figure for reference.

Effects of Thermal Deformation on Slider Flying Height

To study the effect of the write-pole-tip-protrusion (WPTP) on the slider flying performance, the detailed deformations on the slider are input to the CML code and the slider flying heights under various conditions are calculated, together with other configuration changes to the slider. The results for the minimum flying height (at the write-pole-tip) under DC write current 20 mA and 50 mA are listed in Table 4.3. It can be observed that the thermal-induced slider deformation indeed reduced the flying height by 0.41nm at 20mA and 0.99nm at 50mA. By comparing with the local protrusions, which are also listed in table 4.4, it is found that the thermal effect on flying height is in the same scale as the local protrusion. This is because the flying height, being the distance between the disk and slider, is determined by many factors including aerodynamic pressures at the air-bearing-surface, which has been varied by the slider body deformation, so that final flying height changes may not be as large as the slider deformation. However, 1 nm change to the flying height can be very significant when the designed operation flying height is already very low, e.g., less than 5 nm in order to achieve areal density of 1 Tera-bit per square inch.

Table 4.4. Thermal effect on slider flying height.

	Pitch (μrad)	Roll (μrad)	FH (nm)	FH changes (nm)	Protrusion (nm)
Original	197.46	-2.05	11.31	-	-
Write Current 20 mA (DC)	196.45	-2.07	10.90	-0.41	1.0
Write Current 50 mA (DC)	194.93	-2.10	10.32	-0.99	2.5

The simulation results for thermal effect on slider flying height are compared with the measured values. The experimental measurements were conducted for the slider flying over a glass disk rotating at 5400 rpm. The details about the experiment have been given in Chapter 3. The comparisons are presented in Figure 4.30, and good agreement between the simulated flying height changes and measured values are observed.

Figure 4.30. Comparison between simulation and experiment on thermal induced slider flying height changes. The glass disk is rotating at 5400 rpm.

4.6 Summary

Analytical studies and numerical simulations have been intensively carried out in this chapter to predict thermal effect on sliders, including the temperature rise, the corresponding slider deformations and the slider flying height changes.

First of all, the point heat source analytical method for the temperature field in a solid body set up a model to analyze thermal effect in a read/write head, which is a most simple model for the thermal analysis so far. It would be useful to other similar problems, especially when the convection heat transfers exist on the surfaces.

By comparing the results between the analytical solutions and numerical simulation, and between the numerical simulations and experimental measurements, it demonstrated that the thermal-induced temperature rise in slider, the slider protrusions on ABS and the slider flying heights can be accurately predicted with proper thermal boundary conditions corresponding to the disk rotation conditions. The results confirm that the maximum thermal effects on the slider occur around the write/read element which generates the Joule heat due to the write current. The capability of predicting thermal effect on the slider performance will be important to development and design new slider configurations in order to control or reduce the thermal effect on flying height changes, which are presented in next Chapter.

Chapter 5

Control of Thermal-induced Slider Deformation and Flying Height Changes

5.1 Introduction

It has been demonstrated by experimental measurements in chapter 3 and numerical simulations in chapter 4 that, in a disk drive, the heat generated in the process of writing data into a rotating disk will induce nano-deformation of the slider flying on the disk, leading to the change of flying height, which is a tiny space in order of nanometer between the slider and disk. In particular, the experimental results and numerical simulations, plotted in the figure 4.30 in Chapter 4, show that by applying a 50mA write current to the slider flying over a disk rotating at 5400 rpm, the FH will reduce about 1 nm, associated with 2.5 nm in the slider crown change and 2.5 nm in local protrusion. In this chapter, a systematical study on how to control thermal-induced fly height changes has been carried out. It is to develop a new design of slider that is less sensitive to the thermal deformation induced by the write current. The objective of the control to be achieved can be highlighted in the following illustration:

The thermal-induced slider deformation and flying height change may be improved by using materials with better thermal conductivity to dissipate more heat and prevent temperature around write/read head from rising. However, the materials with better thermal conductivity often do not have the expected mechanical hardness, wear resistance, and electrical conductivity for the application in magnetic disk drives. The present study attempts to solve the problem by modifying configuration and geometry of the slider ABS such that the slider flying height becomes less sensitive to the temperature rise around the write/read area, though the overall thermal deformation of the slider still exists. This is achieved by looking into dynamics of the slider responding to various ABS designs, including the sensitivity of flying height to the slider crown, aerodynamic force analysis on ABS, and optimal study of ABS designs. The study in this chapter is based on numerical simulations by using the slider air bearing design and evaluation software - the CML code from University of California, Berkeley. The CML code is the industry standard and a proven code for the evaluation and comparison of slider designs. The slider under the study is the same as that shown in Figures 3.3 and 3.4 in Chapter 3. Basic slider parameters at zero write current are listed in Table 5.1, based on the simulation results by the CML code. (Q. H. Zeng 1999; L.

Wu 1999; L. Wu 2001).

Table 5.1. Simulation parameters for the slider in zero write current

Definition	Value
Dimension: Length×Width×Height (mm)	1.25×1×0.3
Crown (nm)	20
Camber (nm)	0
Rail Recess (micron)	0.1
Base Recess (micron)	1.6
Gram Load (gram)	2.5
Disk Speed (rpm)	5400
Flying height (nm)	11.3

The ABS of the slider under study is shown in Figure 5. 1. It is divided into 2 parts along the slider length direction, called leading part and trailing part. The external force from the suspension is called gram load which exerts on the center of the back side of the slider. The gram load from the suspension is 2.5 gram which is an industry standard setting from suspension, while the gravity force on the slider is in an order of 0.001 gram, and is negligible comparing with the gram load 2.5 gram.

Figure 5.1. (a) A schematic illustration of head-disk interface, and (b) the ABS which is the side facing the disk.

5.2 Crown Sensitivity Analysis

The thermal deformation induced in a slider can be manifested by two parameters: one is the local protrusion around the write/read head area; the other is the slider crown which is a parameter to characterize the overall ABS profile of the slider. The details about the crown are discussed in section 3.3.3 and shown in Figure 3.11. It is much more convenient to take the slider crown, than local protrusion, as the input parameter

to software CML for calculating slider flying height and air pressure distributions on ABS. The flying height of the slider may vary with the change of crown, and the flying height of different ABS design may have different sensitivity to the change of the crown (J. P. Peng, 1996). The flying height sensitivity to the slider ABS crown is analyzed here for the slider shown in Figure 5.1. This is achieved by calculating FH using CML under various crown values. It should be pointed out here that, in order to have a better view on how the crown change affect the forces on the slider ABS, the slider crown changes have been enlarged in this study. The experimental results presented in Chapter 3, Figure 3.12, shows that by applying 50mA write current, the crown is reduced 2.6nm from about 18.6nm to 16nm. In this chapter, the crown changes are assumed in a range from -10nm to +10nm. Table 5.2 lists some typical results for the flying attitudes of the slider at three crown values: initial crown 20 nm, reducing to 10 nm and increasing to 30 nm, respectively. It is observed that both the FH and the pitch angle of the slider increase with bigger crown values. The last column in the table lists the stiffness of the slider in FH direction, which also changes at large crown value. The unit for force is gram (g) and the unit for stiffness is gram per nanometer (g/nm).

Table 5.2. Flying attitude of the slider with different crown values

Crown (nm)	Pitch (μrad)	FH (nm)	FH stiffness (g/nm)
10	177.68	9.4	0.155
20	197.46	11.3	0.153
30	216.80	13.2	0.126

Figure 5.2 shows the flying height variation due to the change of the crown of the slider, the variation of the crown ranges from -10 nm to 10 nm, corresponding to the crown value of 10 to 30 nm. It is observed that the change of the flying height has a linear relationship to the change of the crown, and the relationship is

$$\Delta(\text{FH}) = 0.179 \times \Delta(\text{Crown}) + 0.0866 \text{ nm.} \tag{5.1}$$

When the slider crown varies from 10 nm to 30 nm, the change of the flying height may vary from -1.703 nm to 1.877 nm accordingly. The slope of the line in Figure 5.2 is $\Delta(\text{FH})/\Delta(\text{Crown}) = 0.179$, which is the sensitivity of FH to the slider crown. Equation (5.1) and Figure 5.2 are the results for the existing slider, and they will be served as a reference, with which the new designs of slider ABS will compare to observe any improvement in reducing the sensitivity.

Figure 5.2. Flying height change vs. crown change. Simulation results from CML software based on the original slider ABS design.

5.3 Dynamic analysis on FH Sensitivity to Slider's Crown Variations

A dynamic analysis has been conducted in this section to examine how the air bearing forces exerting on the slider air-bearing-surface and how the air bearing forces change, associated with the crown change, affect the flying height. So as to establish a guideline for new design of ABS in order to minimizing the sensitivity of FH to the slider crown changes.

5.3.1 Forces on Slider ABS

Figure 5.3 (a) shows the forces and their directions on the slider ABS. The slider is flying at certain FH when the positive air bearing force, negative air bearing force and gram load are balanced (Ma et al., 2005). These positive and negative pressure regions are designed to balance the downward force of the suspension gram load in a way that they lift the read/write head to the desired FH. Figure 5.3(b) shows the ABS and areas of positive and negative forces. The rail of slider recess (red color in Figure 5.3(b)) forms a cavity (gray color) at the centre area of slider, which generates a negative air pressure (below atmospheric) pocket that pulls the slider closer to the disk ABS. The shallow steps/pads (green color) are a little higher than the red color parts, and the configuration allows airflow to pressurize the ABS surface, so as to lift the slider and its magnetic element away from the disk surface. The air bearing force on the ABS can be calculated by the industry standard CML code with a given ABS design and disk

rotating speed. A typical result of air pressure distribution on ABS is illustrated in Figure 5.3(c), for a 25 mm radius disk rotating at 5400 rpm with crown 20 nm.

Figure 5.3. The slider, ABS and air bearing force distributions. (a) Force directions on ABS, (b) areas of positive forces and negative forces, and (c) air pressures distributions calculated by CML software, indication negative pressures at centre part of ABS.

By using CML software, it can tell the air bearing force center based on the force moment analysis. For a selected area, for example the tailing pad, the positive force on this pad generates a moment (related to the gram load point). This moment is going to be balanced by the moment on the other pads, together with the moment from negative air bearing force. Based on these moments, a force center for the force on this trailing pad can be calculated. In Figure 5.3(b), the slider length is marked from 0 to 1.25 mm, and the centers of air bearing force in the following analysis are referred to the positions in the slider length direction.

Table 5.3 lists the total positive, negative forces and their exerting points on entire slider ABS with different slider crown values and corresponding FHs. Since the all air bearing forces and flying height will change simultaneously with the slider crown variations, it would be very useful and informative to the new ABS designs to observe how the air bearing forces change if FH and pitch angle are fixed without following crown variations. This can be achieved in the CML simulation and the results are listed in the last two rows in Table 5.3.

It is observed from Table 5.3 that both positive and negative forces, together with their exerting centers do not change much when the slider crown is reduced 50% or increased 50%. On the other hand, it is seen that in order to maintain the same flying height at 11.3 nm achieved at 20nm crown, the positive force on ABS should be reduced

by 8.7% from 5.60g to 5.11g when the crown is reduced from 20nm to 10nm, and the positive force on ABS should be increased by 8.6% from 5.60g to 6.08g when the crown is increased from 20nm to 30nm. It is not observed much change in the negative forces in these cases.

Table 5.3. Force analysis for different crown values of the slider

Crown (nm)	FH (nm)	Positive force (g)	Center of positive force (mm)	Negative force (g)	Center of negative force (mm)
10 ($\Delta = -10$)	9.4	5.70	0.700	-3.20	0.760
20 ($\Delta = 0$)	11.3	5.60	0.696	-3.10	0.758
30 ($\Delta = +10$)	13.2	5.50	0.694	-3.00	0.756
10 (fix FH)	11.3	5.11 (-8.7%)	0.688	-3.10 (0%)	0.760
30 (fix FH)	11.3	6.08 (+8.6%)	0.706	-3.10 (0%)	0.762

The point where the external gram load is exerted is considered to be at the dynamic center of the slider. The slider can rotate around the gram load point in both the pitch and roll directions. Crossing the gram load point, the slider air-bearing-surface is divided into leading part and trailing part. The trailing part and leading part are indicated in Figure 5.3(b). In order to have a better understanding on the air bearing forces variations with the slider crown, the air bearing forces are also divided into the trailing part and leading part accordingly. The similar simulations for the results listed in Table 5.3 are repeated for the positive and negative forces in the trailing part and leading part respectively. Table 5.4(a) and Table 5.4(b) show the changes of the air-bearing forces and the corresponding force exerting points at the leading part and the trailing part of the

slider, associated with the slider crown changes from 10 nm to 30 nm. The last column in Table 5.4(b) is the force at the trailing pad which is indicated in Figure 5.3(b).

Table 5.4. (a): Forces and force loading points at the leading part

Crown (nm)	Positive Force (g)	Center of Positive Force (mm)	Negative Force (g)	Center of Negative Force (mm)
10($\Delta = -10$)	3.01	0.308	-0.94	0.549
20($\Delta = 0$)	2.96	0.309	-0.92	0.549
30($\Delta = +10$)	2.91	0.309	-0.90	0.549
10 (fix FH)	2.76 (-6.75%)	0.309	-0.90 (-2.2%)	0.549
30 (fix FH)	3.14 (+6.08%)	0.314	-0.89 (-3.2%)	0.549

Table 5.4. (b): Forces and force loading points at the trailing part

Crown (nm)	Positive force (g)	Center of positive force (mm)	Negative Force (g)	Center of negative force (mm)	Positive force (trailing pad) (g)
10($\Delta = -10$)	2.69	1.134 (+0.004)	-2.26	0.847 (+0.001)	2.18
20($\Delta = 0$)	2.64	1.130	-2.18	0.846	2.10
30($\Delta = +10$)	2.59	1.126 (-0.004)	-2.10	0.845 (-0.001)	2.04
10 (fix FH)	2.35 (-11.0%)	1.133	-2.20 (+0.9%)	0.847	1.89 (-10.0%)
30 (fix FH)	2.94 (+11.3%)	1.126	-2.21 (+1.3%)	0.847	2.30 (+9.5%)

The simulation results presented in Tables 5.4(a) and 5.4(b) show that:

- 1) On the leading part of ABS, both positive force and negative force, together with their exerting points do not change much along with the variation of the crown from 10 nm to 30 nm. However, in order to maintain the same flying height at

11.3 nm achieved at 20nm crown, the positive force on the leading part should be reduced by 6.75% for the 10nm crown and increased by 6.08% for the 30 nm crown, while changes of negative force are relatively less in these cases.

- 2) On the trailing part of ABS, the required changes on the positive force are about 11% in order to maintain the same flying height at 11.3 nm achieved at 20nm crown, which are much higher than that required on the negative force (about 1%). Besides, the changes of positive force are mainly contributed from the positive force generated on the trailing pad, which is indicated in the last column in Table 5.4(b).
- 3) Also on the trailing part of ABS, when the slider crown changes by ± 10 nm from 20 nm, the positive centre moves by ± 4 μm , while the negative force centre moves only ± 1 μm .

5.3.2 Understanding of FH change based on the force analysis

In an equilibrium flying state, the slider is balanced by all forces including the air bearing forces and the gram load from the slider suspension, and all moments generated by these forces. The flying height change consists of two parts: one is from the vertical position change, and the other is associated with the pitch angle change due to the slider rotation. It has been observed from Table 5.3 that if the slider flying height and pitch angle are fixed (assumed to be hold by an external force), the crown change from 20nm to 10nm will result in a decrease of positive air bearing force $\Delta F = 5.60\text{g}$ -

5.11g = 0.49g, while the negative air bearing force remains unchanged. In this case, the gram load from the suspension will push the slider downwards to the disk. The situation can be illustrated in Figure 5.4. The displacement of slider in FH direction pushed by the gram load can be estimated by

$$\Delta FH = \frac{\Delta F}{k_s} = \frac{0.49}{0.155} = 3.16 \text{ nm (nm)}, \tag{5.2}$$

where $k_s = 0.155 \text{ g/nm}$ is the slider stiffness in flying height direction, which is calculated by CML for crown = 10nm listed in Table 5.2.

Figure 5.4. Illustration showing that the unbalanced gram load pushing the slider (with the same pitch angle) down to reduce the flying height.

The calculation by equation (5.2) shows that the flying height would change 3.16 nm when the slider crown reduced from 20nm to 10nm. The actual change, listed in Table 5.2 is less, 11.3nm – 9.4 nm = 1.9nm. This can be understood from the slider rotation. As shown in Table 5.3, the pitch angle of the slider is also reduced when the crown reduced from 20nm to 10nm, so that the slider trailing edge will move upwards accordingly to increase the flying height. At end, the overall flying height change becomes less than that given by calculation in equation (5.2).

From analysis above, we may summarize that, for the case of crown reduces from 20 nm to 10 nm, (i) the reduction of the positive air force on ABS causes the flying height change, and (ii) the reduction of the slider pitch angle, following the crown reduction, will ease the flying height changes, but the amount is not enough to compensate the overall flying change.

5.4 ABS modifications to reduce the flying height sensitivity to crown variation

From the force analysis and moment analysis, it is seen that, following the crown reduces, the air bearing forces on slider ABS are re-distributed, which may lead to reduction of the positive force to decrease the flying height, and reduction of pitch angle to increase the flying height. A comparative study has been conducted for different designs, varying one parameter or configuration each time and calculating the pitch angle and FH changes. Since the positive air bearing forces, which push the slider away from the rotating disk, are generated by the pads of ABS, the study starts from the ABS pad size effect.

5.4.1 Effect of the trailing pad size

The simulation results listed in Table 5.4(b) show that most of positive forces on the trailing part of slider are contributed by the trailing pad, which also generate moment to

rotate the slider counter-clockwise and reduce the pitch angle. The sizes of the trailing pads (top surface) are modified by reducing the length to 100 μm and increase the length to 300 μm , as shown in Figure 5.5, denoted as slider (a) and slider (c) respectively, together with the original design (b). The changes of the pitch angle and flying height following the crown reducing from 20nm to 10nm are calculated by CML and results are listed in Table 5.5. It is observed that, by reducing the size of the trailing pad, the pitch angle is reduced more and flying height is increased less among three pad sizes, which should be considered in the new design.

Figure 5.5. Trailing pad size effect on sensitivity of pitch angel and flying height to crown

Table 5.5. Trailing pad size effect on the flying height and forces analysis

Slider	Crown (nm)	Pitch (μrad)	FH (nm)	Change of pitch (%)	Change of FH (%)
(a)	20	195.3	7.0		
	10	175.2	6.0	-10.3	-14.3
(b)	20	197.5	11.3		
	10	177.7	9.6	-10.1	-15.0
(c)	20	198.1	12.0		
	10	178.5	10.0	-10.1	-16.7

5.4.2 Effect of leading pad size

The sizes of the leading pad are also modified in this comparative study. As shown in Figure 5.6, slider (b) is the original design, slider (a) is of smaller leading pad and slider (c) is of larger leading pad. The changes of the pitch angle and flying height following the crown reducing from 20nm to 10nm are calculated by CML and results are listed in Table 5.6. It is observed that, by reducing the size of the leading pad, the pitch angle is reduced more than that by increasing the pad size, but in the same time flying height is also reduced more than by increasing the pad size. On the other hand, by increasing the leading pad size, the pitch angle is reduced less and the flying height is also reduced less, comparing to the original design. It is therefore concluded that changing the size of leading pad does not help in reducing pitch angle and increasing flying height simultaneously.

Figure 5.6. Effect of leading pad size.

Table 5.6. Leading pad size effect on the flying height and forces analysis

Slider	Crown (nm)	Pitch (μrad)	FH (nm)	Change of pitch (%)	Change of FH (%)
(a)	20	164.8	11.4		
	10	145.6	9.6	-11.5	-15.8
(b)	20	197.5	11.3		
	10	177.7	9.6	-10.1	-15.0
(c)	20	244.5	11.8		
	10	225.2	10.2	-8.2	-13.6

5.4.3 Shifting force centers and reducing trailing pad

Since the slider pitch angle is determined by the overall moment applied on it, which depend not only the forces, but also the exerting points (force centers) of these force related to the rotation point, the force centers are modified to examine in a new design to observe the effect on the performance. As illustrated in figure 5.7, the positive force generated by the leading pad produces a negative moment to increase the pitch angle, and the positive force generated by the trailing pad produces a positive moment to reduce the pitch angle. The rotation point is the gram load point at the slider center. By shifting both forces towards the trailing edge, the negative moment will be reduced and the positive moment will be increased. The modification of the slider ABS is shown in Figure 5.8, in which, the leading pad is moved by 40 μm towards the trailing edge. The original pads positions are shown by the white dashed lines. Since the smaller trailing pad would reduce the pitch angle, according to the study in 5.4.1, and the trailing pad in

the modified ABS is shortened from one side from 250μm to 100μm, so that the total area is reduced, and in the same time the force center is shifted towards the trailing edge.

Figure 5.7 Schematic illustrations of the forces and force centers.

Figure 5.8. Modified Air bearing surface by shifting leading pad and trailing pad.

The performance simulation for the modified ABS has been conducted by CML and the results are listed in Table 5.7, comparing with the original design in terms of flying height changes following with the crown variations. It is seen that the flying height in the modified ABS has less sensitivity in following the slider crown changes, and improvement is 31% when the slider crown reduced from 20nm to 10nm.

Table 5.7. FH change and crown sensitivity for original design and modified design

	Crown (nm)	Pitch (μ rad)	Pitch change %	FH (nm)	FH change %	FH change Improvement
Original design	20	197.5		11.3		
	10	177.7	-11.14	9.6	- 17.7	
Modified design	20	192.09		10.9		
	10	172.06	-11.64	9.6	- 13.5	31%

5.5 Dual steps air bearing surface design

It is very encouraging to see that, from the results presented in section 5.4.3, by moving the both leading pad and trailing pad towards the slider trailing edge, the flying height change has been reduced by 31% when the slider crown is changed from 20nm to 10nm, comparing to the original ABS design. However, due to the configuration limitation of ABS, the leading pad cannot be further moved towards the trailing edge. Besides, the trailing pad cannot be narrowed too much. The amount of positive force will be too small, otherwise, to support the slider head.

5.5.1 Design of dual steps ABS

A novel design is proposed in this study. The new ABS design is to remain the original trailing pad unchanged, but put an addition layer on top of it. Besides, the leading pad has been moved $30\mu\text{m}$ towards the trailing edge. The new design is illustrated in Figure 5.9, and is called dual shallow step ABS. The additional layer, 10nm in step height, is fabricated from surface of the original trailing pad which has step height around 160 nm . The size of this additional layer is about $45\mu\text{m} \times 150\mu\text{m}$, which is much small than the original trailing pad. The center of this layer is only $42.5\text{ }\mu\text{m}$ from trailing edge. The dual steps design is based on following two mechanisms:

- (1) The additional layer (or step) will generate a positive force around the slider trailing edge. Since this layer is very close to the trailing edge, the moment corresponding to the positive force on the layer will produce a positive rotation to reduce the pitch angle, so as to increase the flying height.
- (2) On the other hand, the large air bearing pressure associated with this layer around the trailing edge, where the write/read head is located, will increase the cooling heat flux in this area, according to equation (4.45). As a consequence, the heat dissipation will be increased to release the heating effect and the local protrusion will be reduced. A smaller local protrusion will of course reduce the flying height change (Han, et. al., 2006).

Figure 5.9. Dual steps design. The blue color is the dual step; the leading pad has been moved 30μm towards the trailing edge.

5.5.2 Performance of dual steps ABS

The performance of dual steps ABS has been evaluated by simulations using ANSYS software to calculate the slider temperature and thermal-induced local protrusion, and using CML software to calculate the air pressure, heat flux and flying height. The slider performance parameters at zero write current are listed in Table 5.8, together with that from the original ABS, to be used as reference.

Table 5.8. Original ABS vs. dual steps ABS. The sliders are flying on a rotating disk at 5400 rpm without write current.

	Original ABS	Dual steps ABS
Dual steps	-	10 nm
FH	11.3 nm	14.2 nm
Pitch angle	197.46 μ rad	195.00 μ rad
Positive force on trailing pad	2.10 g	2.85 g

Firstly, the sensitivity of flying height to the slider crown change is plotted in Figure 5.10. It can be seen that the slope corresponding to the dual steps ABS becomes

$$\Delta(\text{FH}) = 0.115 \times \Delta(\text{Crown}) + 0.1412 \text{ nm}, \tag{5.3}$$

Figure 5.10. Flying height change vs. slider crown change for both original ABS and dual steps ABS. Simulation results from CML code.

and the sensitivity of FH to the crown change becomes $\Delta(\text{FH})/\Delta(\text{Crown}) = 0.115$, which has been reduced by 55.6% comparing to the original ABS. This indicates that flying height will be reduced less following the slider crown changes in dual steps ABS.

The air pressure distribution and associated heat flux along the centerline near the trailing edge are plotted in Figure 5.11 and Figure 5.12 respectively. It is seen that, by adding the small step on the trailing pad, the air pressure is increased significantly, from the maximum pressure 11.7 atm near the trailing edge on original ABS to the maximum pressure 23.2 atm on the dual steps ABS. The high air pressure on the additional layer will not only increase the positive force to lift up the slider, but also produce a count-clockwise rotation moment on the slider to reduce the pitch angle, which will ease the flying height reduction due to the slider deformation. Besides, the high air pressure increases the heat flux dissipated by air flow around the write/read head. This is shown in Figure 5.12. It can be seen that the heat flux is almost doubled on the dual step, comparing with that on the original trailing pad. The high heat flux has been extended from the dual step into the inner part of the ABS, which will increase the overall heat loss on ABS.

From thermal management point of view, the high heat dissipation flux around the write/read head area improve the heat dissipation and therefore ease the temperature rise due to the heat generated in write/read head. By using the heat flux on ABS

obtained from CML software, the temperature distributions in the sliders are calculated by ANSYS, together with the thermal-induced slider deformation, manifested as local protrusions. The results are plotted in Figure 5.13 for the ABS temperature rise and Figure 5.14 for slider local protrusions respectively.

Figure 5.11. Air pressure distributions near the slider trailing edge along the centerline for original ABS and dual steps ABS. The simulations are conducted by using CML code at write current 50mA and disk rotation speed 5400 rpm.

Figure 5.12. Heat flux distributions near the slider trailing edge along the centerline for original ABS and dual steps ABS. The simulations are conducted by using CML code at write current 50mA and disk rotation speed 5400 rpm.

Figure 5.13. Temperature rise on ABS associated with write current 50mA near the slider trailing edge along the centerline for original ABS and dual steps ABS. The simulations are conducted by using ANSYS software at write current 50mA and disk rotation speed 5400 rpm.

Figure 5.14. Thermal induced local protrusions associated with the write current near the slider trailing edge along the centerline for original ABS and dual steps ABS. The simulations are conducted by using ANSYS software at write current 50mA and disk rotation speed 5400 rpm.

It is clearly shown in Figure 5.13 that the maximum temperature rise on the dual steps ABS has dropped from about 14 K from the original ABS to about 6 K, the drop is 133%. Correspondingly, the maximum local protrusion over the trailing pad has been reduced from original 2.5nm to 0.86nm. The reduction of 190% has been achieved for the slider local protrusion associated with the write current induced deformation.

Finally, the performance parameters of the dual steps ABS under write current 50mA and disk rotation speed 5400 rpm are listed in Table 5.9, including the maximum air bearing pressures, maximum dissipation heat flux, maximum temperature rise, etc, together with the flying height changes. It is shown that, when a write current 50mA is applied on the slider write/read head, the flying height of original ABS will reduce 0.99nm, or 8.7%. While at the same write current 50mA the proposed dual steps ABS will produce only 0.05nm, or 0.35%, in flying height reduction. The improvement is about 25 times. Therefore, the dual steps ABS design can solve FH changes induced by the write current.

Table 5.9. Performance of the dual steps ABS by the simulations at 50 mA and disk rotation 5400 rpm

Slider parameters	Dual Steps ABS	Original ABS	Improvement %
	(value at 0mA)	value at 50mA	
Crown (nm)	(20)19.6	(20) 18.7	
Max. air pressure (atm)	23.2	11.7	+98.3
Max. heat flux (W/m ²)	1.7x10 ⁶	0.8x10 ⁶	+112.5
Max. temperature rise (K)	6	14	-57.1
Protrusion (nm)	(0)0.86	(0)2.5	-65.5
Pitch angle change (μrad)	(195.00 → 194.17) -0.4%	(197.46 → 194.93) -1.3%	3 times
Flying height (nm)	(14.08)14.03	(11.31)10.32	
Flying height change (%)	-0.05nm (-0.35%)	-0.99 nm (-8.75%)	25 times

5.6 Summary

A systematical investigation has been carried out on how to reduce the effect of thermal-induced slider nano-deformation on the flying height during the write/read process. Effort has been made on modifying the air bearing surface design of the slider so as to minimize the flying height reduction caused by such nano-deformation. The air bearing force analysis shows that the sensitivity of flying height to the slider crown change can be reduced by shifting the leading pad towards the trailing edge and reducing the trailing pad size. A dual shallow-step ABS design concept is, therefore, proposed which adds a small and thin layer on the original trailing pad of the slider. The new design is based on the results from the air bearing force analysis. It also takes into account the fact that a high air bearing pressure enhances the heat dissipation and, therefore, reduces the thermal formation. The performance of the dual shallow-step ABS design has been evaluated by numerical simulations. The results show that the flying height with such dual step ABS design can remain almost unchanged even when a 50mA write current is applied to the slider.. Dual steps ABS design significantly reduced the thermal-induced nano-deformation and flying height change. Such a design concept attracted a noticeable attention in industry and a lot of research work was carried on after the results of author's project is released. Currently, the dual-shallow steps ABS design concept has already been widely used in hard disk industry and high percentage of the latest disk drives (2008 onward) are using sliders with dual or multi shallow step configuration of slider's trailing pad .

Chapter 6

Conclusions and Outlook

6.1 Conclusions

A systematic study has been conducted on thermal-induced nano-deformation of slider body and the flying height change caused by such a nano-deformation. The study includes experimental measurements, analytical calculations and numerical simulations on the slider temperature rises, deformations and flying height changes. Based on the measurements and simulations, a new design of slider ABS has been proposed and numerically tested by industry standard evaluation code. Results indicate that the new design can minimize the thermal effects on slider deformations and flying height changes.

The following are major conclusions drawn from this study.

1. The Joule heat associated with the write current indeed causes temperature in the slider head to rise up to 66-68°C in the static conditions, and 11-16°C in the flying condition, depending on the write current and disk rotation speed. The temperature rise leads to slider deformation which can be manifested by both local protrusions and overall crown changes. The author observed that the slider crown value

always reduces with the writing induced heating. The author also proposed and presented proper explanation for such a newly observed phenomenon. Such a kind of pioneering work in this project served as a useful reference to other researchers and the topic becomes a hot topic in recent years.

2. By direct measurements, the slider flying height changes associated with the write current induced thermal effect are quantified. The investigations aim at the challenges and solutions for the realization of future ultra-high density magnetic recording technology. The flying height can drop up to 1nm or more for the sliders under the present study, depending on the write current and disk rotation speed. Such an amount of flying height drop is not acceptable for advanced magnetic disk drives as the allowed flying height variation should be 10% of the flying height, as the technology is moving towards 3.5 nm flying height which can only tolerate 0.35 nm flying height change.

3. The Green function corresponding to a point source for temperature distributions in a uniform material with convection boundary condition on one surface has been obtained in analytical forms. It is the only method to solve the heating induced temperature field analysis analytically. The Green function has been applied to solve the slider body temperature associated with the heat generated in the read/write head which has been approximated as a block heat source. The analytical results are compared with the numerical simulations by ANSYS. The

Green function may be used in other similar problems which have convection boundary conditions.

4. The numerical simulations by combination of the ANSYS software for slider temperature and deformation and the CML code for slider flying height analysis are validated by experimental data. It is demonstrated that the numerical simulations are capable of calculating and predicting the writing induced thermal effect on slider, in terms of temperature rise, deformations and flying height changes.
5. The positive forces on slider ABS generated by the leading pad and the trailing pad have greater effect on the flying height changes than the negative forces created by the cavity area of slider's ABS. By shifting the leading pad towards the ABS center and reducing the trailing pad size, the amount of flying height change can be reduced. The mechanism for such an improvement is investigated and the improvement comes from reduced slider's pitch angle which lifts up the slider and reduces the flying height sensitivity to the thermal-induced nano-deformation.
6. The investigations conclude that the thermal-induced flying height changes can be significantly reduced by a proper design of the slider air bearing surface. The author proposed dual shallow-steps ABS design approach, in which a small and thin layer is added on the original trailing pad. Such an approach proved to be an

effective method to reduce flying height change caused by thermally induced nano-deformation. The concept is proposed in 2003~2004 by the author and author's team. Such a concept has been widely accepted by industry and has been implemented in disk drives manufactured in 2008 onward.

7. The dual step approach proved to be an effective way to further increase the dissipation of thermal energy generated by writing operation. The additional shallow step on the trailing pad increases the air pressure significantly around the read/write head to dissipate the heat generated by the write current and, therefore, reduces the amount of thermally induced nano-deformation. Furthermore, such a design also increases the air bearing stiffness which reduces the flying height change caused by the nano-deformation and environmental shock and vibration.

6.2 Outlook

It has been demonstrated in this study that the stability of a slider flying over a rotating disk is a complicated thermal-mechanical problem, involving in heat transfer, mechanical structure deformation and aerodynamics. The slider flying height can be controlled through a proper design of the slider ABS. It is proposed to have a more sophisticated design package for slider ABS, taking into account simultaneously of the heat generation, dissipation, aerodynamic forces inside the nanometer gap between ABS and rotating disk, together with dynamics of the slider.

It is hoped that the better understanding of the thermal-induced flying height changes and the technique developed on slider ABS designs in the present study can contribute to the new generation of hard disk drives which have high requirement on stabilities of slider flying height.

The investigation reported in this work has been further extended to the concept of thermal nano-actuator for flying height control. In fact, disk drives with such thermal actuator are in production nowadays.

Publication List

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