Contact Force and Frictional Heating due to “Large” Particles in the Head Disk Interface

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ABSTRACT

Particles in the head disk interface may cause large contact forces acting on the slider as well as thermal asperities in the read/write signal. This is especially true for the close spacing required for 1Tbit/in^2. In this paper, a three-body contact model is employed to study the effects of a particle entrapped between a slider and disk. A criterion for determining a particle’s movement pattern is proposed. The study of particles in the head disk interface shows that large particles are likely to slide between the slider and disk interface, and the particles going through the trailing pad of an air bearing slider cause severe contact forces on the slider and generate large heat sources. The frictional heating study shows that the temperature around the magnetoresistive (MR) head increases about 5 ^{0}C for a single 200nm particle passing through the trailing pad of the slider. The effects of the particle size, disk material and friction coefficient are also studied. It is found that the disk and slider materials and the frictional coefficient between the materials largely affect the contact force acting on the slider by an entrapped particle as well as the temperature rise at its contact region. It is also found that the friction coefficient largely affects a particle’s movement pattern in the head disk interface.

Keywords: Air Bearing, Particle Flow, Contact, Frictional Heating.

1. Introduction

With the evolution of magnetic recording disk technology the flying height of the sliders has decreased dramatically. Currently, the minimum flying height for $1Tbit/in^2$ is targeting as low as 5 nm. With such narrow spacing between the slider and disk surfaces, the flow of particles and their contamination on slider surfaces and their effects in the head disk interface become a major concern. For a particle entering the air bearing its possible effects include modulation of the flying height, abrasive wear and mechanical scratching of the magnetic disk surface, and thermally induced spikes in the read-write signal as illustrated in Fig. 1. Flash events introduced near MR transducers modify the MR signal because of the dependence of the coil's electrical resistance on temperature, while mechanical scratching on magnetic disk surfaces may cause permanent data loss. Those effects depend on the size and other properties of the particles as well as their interaction with the slider and magnetic disk surfaces. Therefore, proper slider design is necessary to reduce the particles' chances of entering the air bearing, contacting the slider and disk surfaces, and contaminating the slider surfaces.

The motion of a particle moving from the leading edge to the trailing edge of an air bearing is quite difficult to describe due to the various forces acting on it. For a particle in the air bearing the forces are dependent not only on the particle's size, density and the air velocity and pressure fields in the air-bearing but also on the relative velocities between the particle and the air-bearing, the particle's speed and the initial entry conditions. Various expressions for determining the forces acting on a particle in unsteady gas flows have been derived by Liu et. al. [1], Saffmann [2] and Chen [3].

Previously, Zhang and Bogy [4, 5] and Shen et. al. [6, 7] studied the contamination of small particles on air bearing sliders. For a slider flying over a rotating disk, one possible phenomenon is that of a large particle falling off the slider, and going into head disk interface. For these large particles entrapped between the air bearing slider and disk surface, the effect on the slider's dynamic performance is more severe for lower flying sliders. The contact force causes the slider's flying height to fluctuate. Therefore, the head media spacing will be modulated, which is critical for 1Tbit/in^2 magnetic hard disk drives.

Recently, Khonsari et al. [8] studied the abrasive failure of hydrodynamic bearings induced by an abrasive particle. By modeling a particle penetrating into two plate surfaces, they predicted the critical particle size causing a scuffing failure. For a particle sliding on a surface under a normal force, one well-known phenomenon is frictional heating [9]. In the head disk interface, one major concern is magnetoresistive (MR) head read back signal change due to the local heating near the head. Chen et. al. [10] studied the thermal dependence of the MR signal on slider flying height. They found that the MR element's resistance changed linearly with temperature change. The temperature rise due to a particle entrapped between the trailing pad of a slider and disk can be quite large.

In this paper we study the effects of relatively large particles in the head disk interface. First, the three-body contact model is employed for a particle entrapped between an air bearing slider and disk. A criterion for determining the particle's movement pattern is also proposed. A detailed study of particles in a head disk interface shows that larger particles are likely to slide between the slider and disk, and particles going through the trailing pad of an air bearing slider cause a severe contact force on the slider and generate large heat flux. The frictional heating study shows that the temperature around the MR head increases for particles passing through the trailing pad. The effects of the particle’s size and disk materials are studied. It is found that, as expected, the disk and slider materials also affect the contact force acting on the slider by a particle.

2. Three-body abrasive modeling

For a particle partially penetrating into a disk surface and scuffing on the slider surface as shown in Fig. 2, the forces exerted by the particle depend on the penetration depths as well as slider and disk materials [8].

Let r_1, r_2 be the contact radii at the particle-slider and particle-disk interfaces, respectively. The normal loads acting on the slider and disk surfaces by the particle are:

$$F_s = \frac{\pi}{2} r_1^2 H_s \tag{1}$$

$$F_D = \frac{\pi}{2} r_2^2 H_D \tag{2}$$

where H_s and H_D are the slider and disk material hardness, respectively. The friction coefficients between the particle and disk and particle and slider are μ_D and μ_s, respectively. Therefore, the friction forces are given as:

$$f_s = \frac{\pi}{2} \mu_s r_1^2 H_s \tag{3}$$

$$f_D = \frac{\pi}{2} \mu_D r_2^2 H_D \tag{4}$$

The contact radii, r_1 and r_2 are determined by the geometrical constraints between the penetration depth and the spacing between the slider and disk surfaces. For two parallel plates, we have

$$h + D_s + D_d = 2R \tag{5}$$

where h is the spacing between the slider and disk surface; D_s is the penetration depth into the slider; D_d is the penetration depth into the disk; R is the particle's radius.

Geometrically,

$$r_1^2 = 2R \cdot D_s - D_s^2\,,\ r_2^2 = 2R \cdot D_d - D_d^2\,. \tag{6}$$

For a particle entrapped between an air bearing slider and disk,

$$F_s = F_D \tag{7}$$

Therefore,

$$\frac{r_2^2}{r_1^2} = \frac{H_s}{H_D} = \alpha \tag{8}$$

Substituting Eq. (7) into the first equation in (6), we obtain

$$\frac{r_2^2}{\alpha} = 2R \cdot D_s - D_s^2 \tag{9}$$

Substituting Eq. (5) into the second equation in (6), results in

$$r_2^2 = \left(h + D_s\right)\left(2R - h - D_s\right). \tag{10}$$

Combining Eq. (9) and (10), we obtain the following equation for the penetration depth on the slider,

$$\alpha\left(2R \cdot D_s - D_s^2\right) = \left(h + D_s\right)\left(2R - h - D_s\right) \tag{11}$$

The solution of this equation is

$$D_s = \frac{R(\alpha - 1) + h - \sqrt{\left[R(\alpha - 1) + h\right]^2 - (\alpha - 1)h(2R - h)}}{\alpha - 1}, \tag{12}$$

which is suitable for $\alpha \neq 1$. For $\alpha = 1$, $D_s = \frac{2R - h}{2}$. The contact radii r_1 and r_2 can be calculated from Eqs. (6) and (9), respectively.

3. Criteria for movement of a moving particle entrapped in a head disk interface

A particle moving in the head disk interface could be sliding or rolling. The movement pattern is determined by the driving moment and resistive moment acting on the particle. As illustrated in Fig. 2, the driving moment for a particle to roll is provided by the friction force, which is determined by

$$M_D = f_s h. \tag{13}$$

The resistive moment preventing a particle from rolling is the moment due to the normal force acting on the slider, which is

$$M_R = F_S e. \tag{14}$$

Here $F_S = F_D = F$, and e is the effective moment arm for the normal force. Assuming that the pressure acting on the particle is uniformly distributed across the contact area,

$$e = \frac{4}{3\pi}(r_1 + r_2) \tag{15}$$

The condition for a particle to roll is

$$M_D = f_s h > M_R = F_S e \tag{16}$$

which becomes

$$\frac{e}{h} < \frac{f_s}{F_S} = \mu_s. \tag{17}$$

where μ_s is the friction coefficient between the particle and slider for the rolling motion. If the resistive moment is larger than the driving moment, the particle will slide along the slider. In this case,

$$\frac{e}{h} > \frac{f_s}{F_S} = \mu_k \,. \tag{18}$$

Therefore, the static friction coefficient is larger than the rolling friction coefficient. The unified criteria for determining a particle's movement pattern are

Particle rolling

$$\frac{e}{h} < \mu_s \tag{19}$$

Particle sliding

$$\frac{e}{h} > \mu_s \tag{20}$$

4. Flash temperature for sliding particles

For a particle sliding on a stationary body, the maximum temperature rise on the stationary body is determined by [9]

$$\Delta T = \frac{2qr_1}{\kappa_s \sqrt{\pi}} \tag{21}$$

where q is the heat flux going into the slider, r_1 is the contact radius on the slider, and κ_s is the slider material's thermal conductivity. In this case, the heat flux going to the slider can be determined by,

$$q = \beta \mu_k U F_S \tag{22}$$

where $\beta = \dfrac{1}{1 + \dfrac{\kappa_P}{\kappa_S}\sqrt{1+Pe}}$ is the heat partition coefficient, $Pe = \dfrac{Ur_1}{2\kappa_P}$ is the Peclet number, and κ_P is the particle material's thermal conductivity.

5. Numerical Results and Discussion

A typical slider is chosen as shown in Fig. 3 for studying the effect of large particles in the head disk interface. The minimum flying height is 9nm with a pitch angle of 134 μrad at the disk location of 23cm with a skew angle of 9.1 degrees. The important spacing between the air bearing surface and disk surface are shown in Fig. 3 at various locations. It is shown that the spacing between the air bearing surface and disk at the leading pad is about 135nm, while the spacing before the leading edge of the air bearing slider is above 400nm. At the trailing edge of the slider, the spacing decreases dramatically to 9.4 nm where the MR element is located. The decreasing gap will induce increasing contact force acting on the air bearing slider as the particle passes through. The material properties of the slider and disk materials used in this paper are given in Table 1. We first consider a particle initially located in front of the leading edge of the slider with coordinates of x=0.0125 mm and y=0.375mm which is illustrated in Fig. 3. The disk material is first chosen to be Aluminum. The particle is assumed to be rigid. The slider material is $(TiC)_{40\%}(Al_2O_3)_{60\%}$. The contact forces acting on the air bearing slider by 180nm, 220nm and 240nm particles as they move along the slider are given in Fig. 4. The maximum contact force is about 2.7 μN for the 240nm particle while it is 1.2 μN for the 180nm particle at the leading pad of the air bearing slider. Also, it is observed that the 180nm particle rolls between the head and disk interface while the 240nm particle slides.

Currently, many magnetic disk drives are using glass disks. For glass, the indentation depth on the slider will be different than for Aluminum for a given rigid particle. Therefore, the contact force acting on the slider will be largely affected by the disk material. Figure 5 shows the comparison on the contact force and thermal spike on the slider by a 240nm particle between a glass and aluminum disk. The contact force is 47 μN when the particle is entrapped between the slider and a glass disk while it is only 2.7 μN for an aluminum disk. This larger contact force also generates a much larger thermal spike (9.3 ^{0}C) on the slider surface for a friction coefficient of 0.2. The flash temperature also depends on the friction coefficient between the slider and particle. Figure 6 illustrates the effect of the friction coefficient on the flash temperature on the air bearing surface. It shows that for a textured slider (μ=0.5) the temperature rise can be above 23 ^{0}C. The friction coefficient also affects the movement pattern of the particle. It is observed in Fig. 6 that the particle begins to slide at x=0.126 mm for the friction coefficient of 0.5. For the friction coefficients of 0.1 and 0.2, the particle begins to slide at x=0.074mm.

For an operating hard drive, many particles will enter the air bearing at the same time. 500 particles with size of 200nm are chosen to enter the air bearing at the leading edge of the slider. These particles have a density of 1.85E3 kg/m^3. At the time of t=0.2, 206 particles are entrapped between the slider and disk surfaces as shown in Fig. 7. The maximum contact force by one particle on the slider is 5 μN. However, the total resultant force on the slider is close to 500 μN at t=0.2. This force is large enough to push up the leading pad of the slider. As time evolves, the particles move toward the trailing pad where the MR element is located. The flash temperature at the trailing pad will cause the MR signal change. It is shown in Fig. 8 that these particles cause a temperature rise of 5 ^{0}C at the center of trailing edge at t=0.95.

Also, the total force and moments acting on the slider fluctuate when these particles pass through the head disk interface. As shown in Fig. 9, the maximum total force acting on the slider occurs when the particles pass the leading pad of the slider because the total number of particles entrapped between the slider and disk surface reaches the maximum value at this location. When most of the particles fly in the recess region of the air bearing slider, the force acting on the slider is negligible as illustrated in Fig. 9. Figure 10 shows the pitch and roll moments acting on the slider by these particles. The roll moment is much less than the pitch moment at all times. Also, the pitch and roll moments reach their maximum values at t=0.2. The contact force and moments created by these particles, as shown in Figs 9 and 10, will strongly affect the slider's flying height and pitch.

6. Conclusions

In this paper a three-body contact model is employed to study the effects of a particle entrapped between a slider and disk. A criterion for determining a particle's movement pattern is proposed. A detailed study of particles in a head disk interface shows that large particles are likely to slide between the slider and disk, and particles going through the trailing pad of an air bearing slider produce severe contact force on the slider and generate large heat flux. The frictional heating study shows that the temperature around the MR element will increase about 5^0C for a single 200nm particle passing through the trailing pad. The effects of particle size, disk material and friction coefficient are also studied. It is found that the disk and slider materials and the friction coefficient have a large effect on the contact force acting on the slider by a particle as well as the temperature rise. A glass disk will have a more severe contact force and thermal spike on the slider by particles in the interface while an aluminum disk will be indented more by the particles than the glass disks.

Acknowledgements

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Nomenclature

R	= the radius of a particle
U	= particle sliding velocity
D_s, D_d	= indentation depths into slider and disk
F_s, F_D	=normal forces acting on slider and disk surfaces
H_s, H_D	=hardness for slider and disk materials
M_D, M_R	=driving and resistive moments for particle rolling
e	=effective arm length for normal force
h	= spacing between slider and disk surfaces
q	=heat flux
x, z	=coordinates

r_1, r_2 =contact radii

β = heat partition coefficient

μ_s, μ_k =friction coefficients

κ_s, κ_P =thermal conductivities

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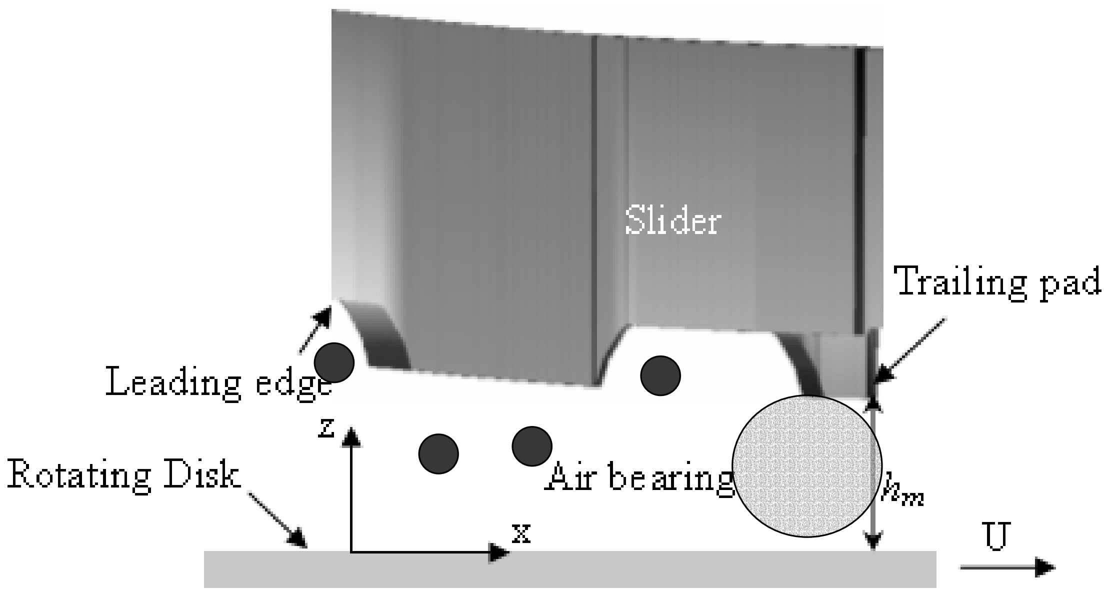

Figure 1. A sketch of slider-disk assembly with particles and Cartesian coordinates.

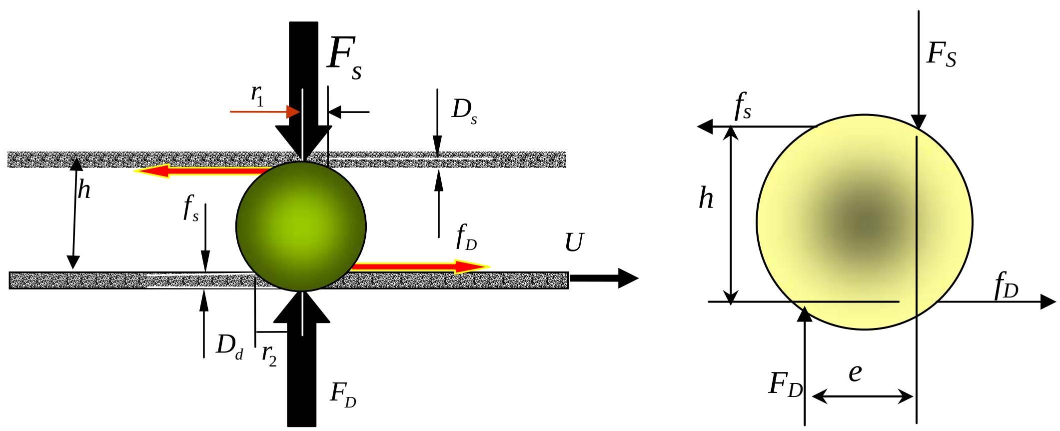

Figure 2. Particle entrapped between two parallel surfaces and force diagram.

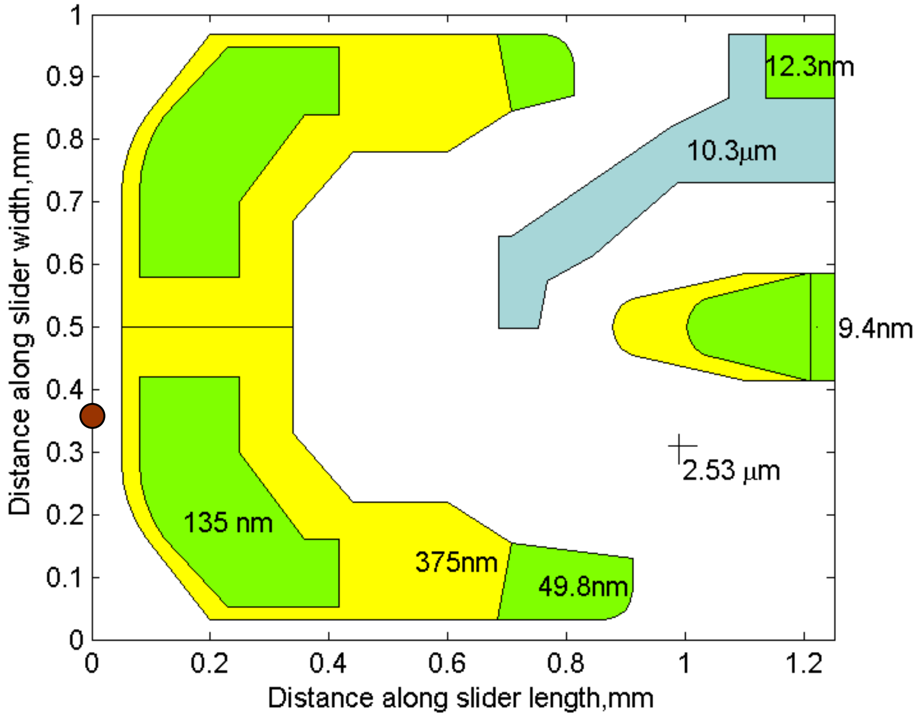

Figure 3. One air bearing slider used for studying large particle effect.

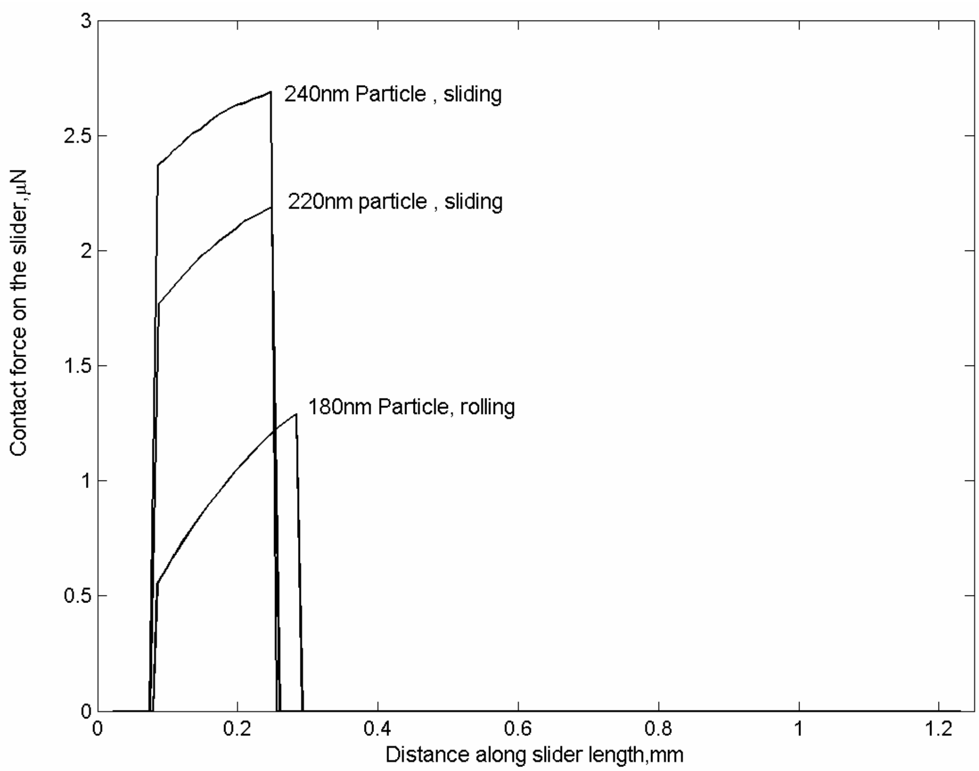

Figure 4. Size effect on contact force by a particle between a slider and aluminum disk.

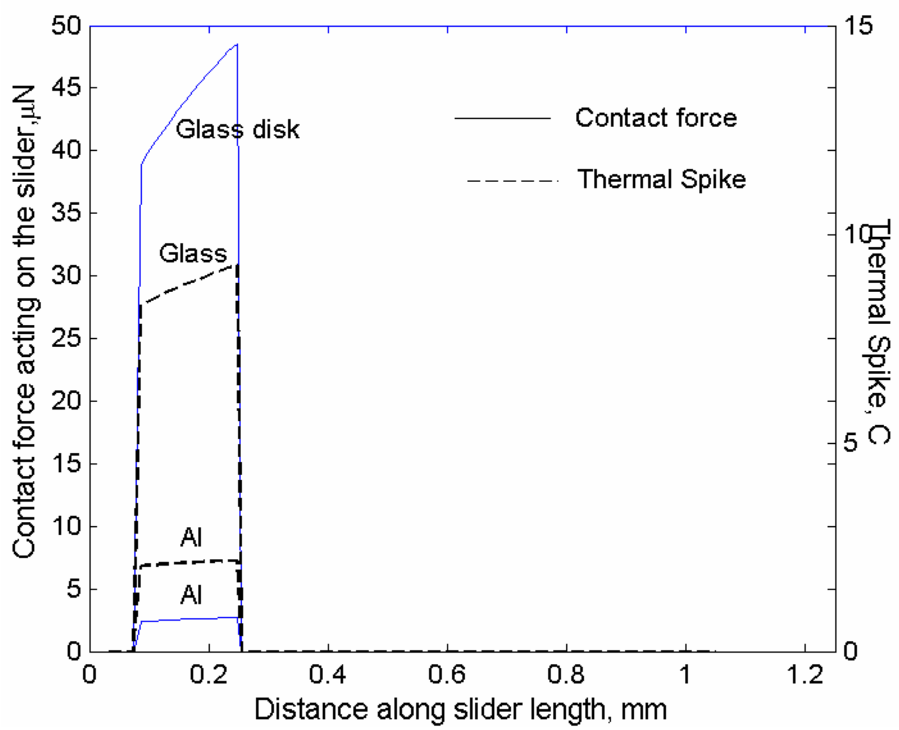

Figure 5. Disk material effect on the contact force and thermal spike on the slider by a 240nm particle.

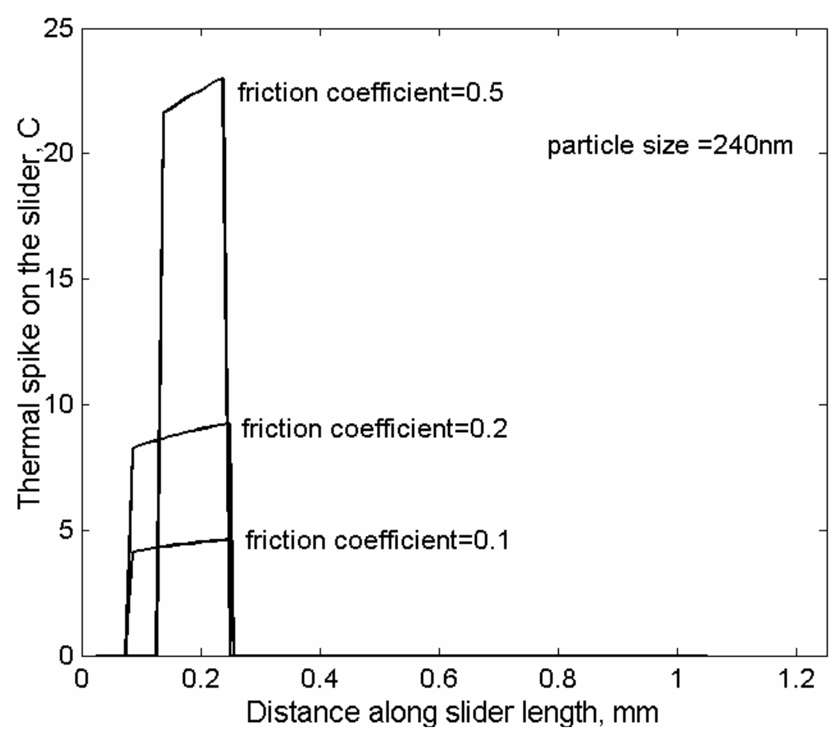

Figure 6. Friction coefficient effect on the thermal spike on the slider.

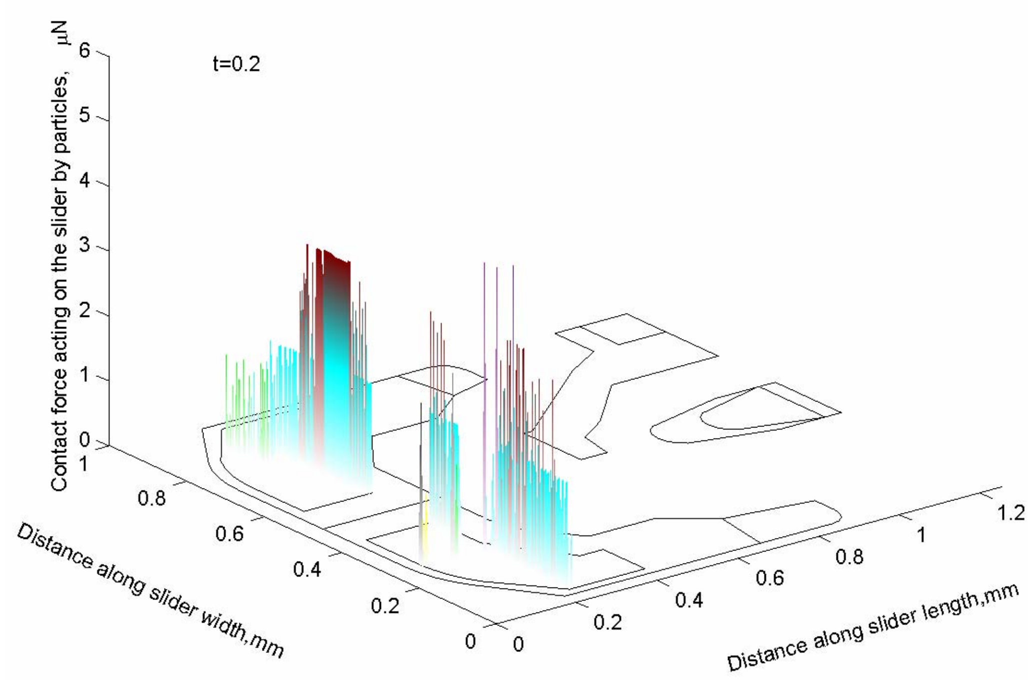

Figure 7. Contact force map acting on the air bearing surface at t=0.2.

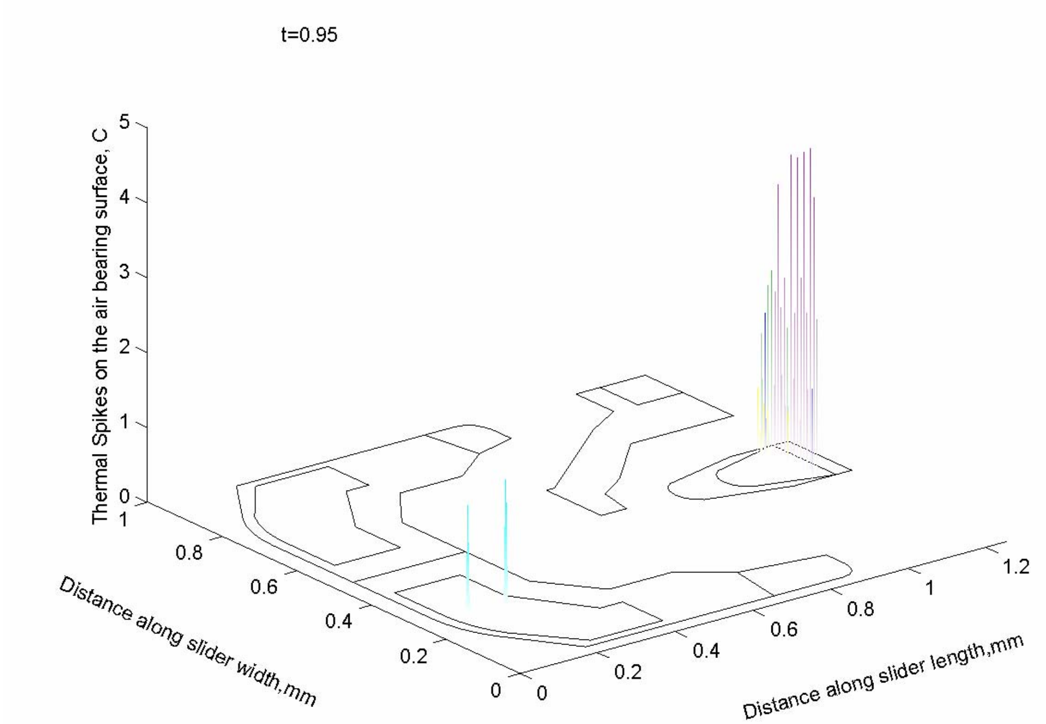

Figure 8. Temperature rise on the air bearing surface at t=0.95.

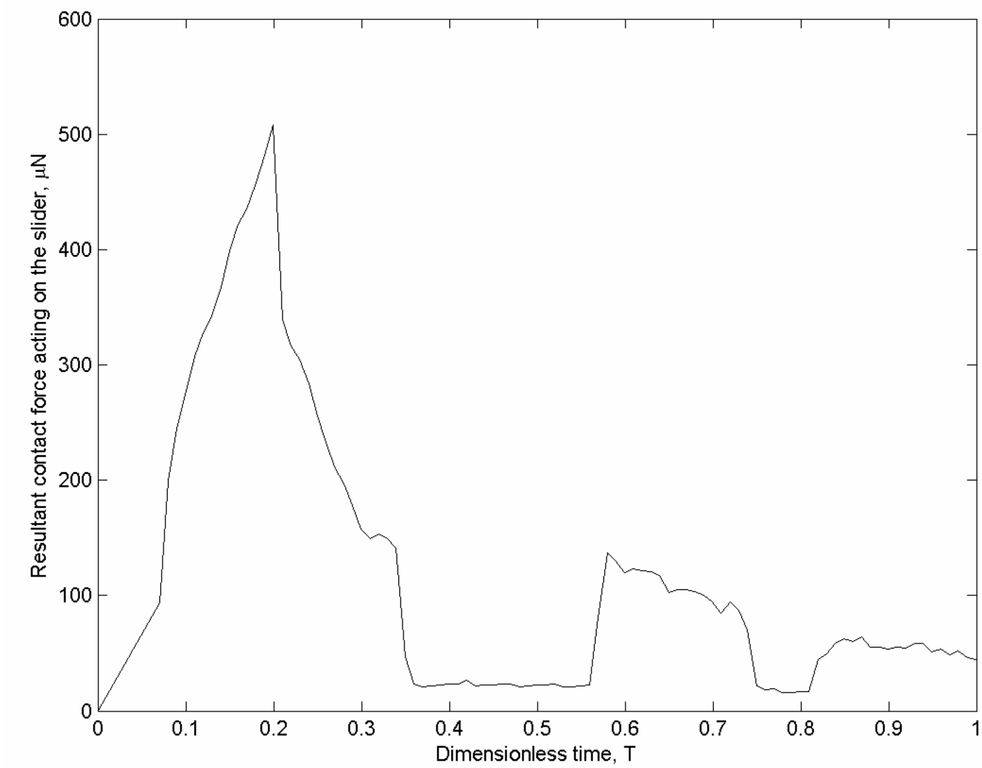

Figure 9. Resultant contact force history acting on the slider.

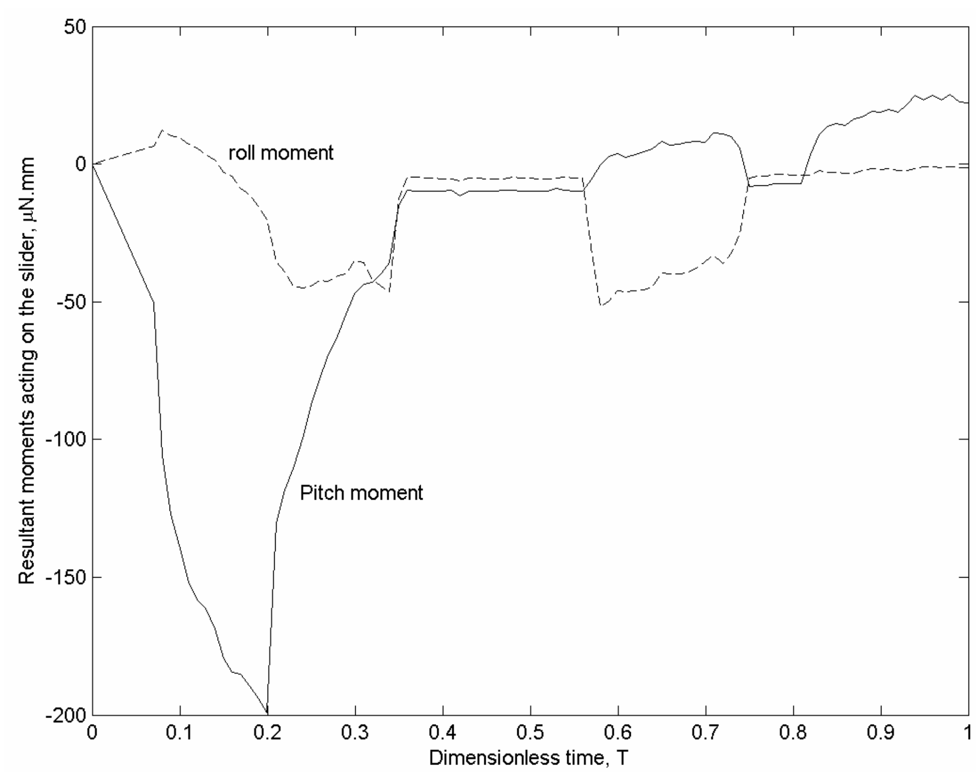

Figure 10. Resultant contact force moments' histories acting on the slider.

Table 1 Material Properties for slider and disk materials

Materials	Hardness (MPa)	Young's modulus (GPa)	Thermal conductivity (W/m-k)
$(TiC)_{40\%}(Al_2O_3)_{60\%}$	2.42E3	4.39E2	27
Glass	4.77E3	68	1.38
Aluminum	1.2E2	69	166.9