A Study of the Thermal Dependence of the MR Signal on Slider Flying State Using a Modified Heat Transfer Model in the Air Bearing

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ABSTRACT

A modified heat transfer model in the air bearing has been developed to study the thermal dependence of the MR signal on the slider's flying height. It is combined with a 3D heat transfer model in the slider body to calculate MR responses to different flying height and skew angles. The simulation results are compared with experimental data, and it is found that the simulation and measurements are in good agreement. It was formerly believed that the thermal influence of the MR signal comes mainly from the flying height change of the MR head, and that MR temperature increases with increasing flying height. It is shown here that this is not always the case. We found that for some air bearing designs, when the flying height is very small(less than the mean free path of ambient air), MR temperature first drops and then increases with increasing flying height. Furthermore, we also found that other flying factors such as skew angle affect the MR temperature. The consistency of the simulation and experimental results shows that the modified model for heat transfer in the air bearing is more accurate than previous models. A theoretical explanation of these phenomena is also provided.

Keywords: MR element, air bearing, thermal mapping

1. Introduction/Motivation

The read-back signal of a magnetoresistive (MR) head can be significantly affected by thermal influences, because the electrical resistance of the MR sensor is temperature dependent. This thermal influence comes mainly from the heat flux between the disk and the MR sensor. It also depends on the MR structure and the flying state of the slider. There have been several studies of the heat transfer mechanism related to MR read back signal disturbances in hard disk drives. Zhang and Bogy [1] studied the heat transfer between the slider and the air bearing, and they derived an expression for heat flux between them using simplified momentum and energy equations in the air bearing. In that study, the mean free path of air was assumed constant and some important terms in the energy equation were omitted. Consequently, the model was inconsistent with the experimental results prescribed in this report.

A 2-D heat conduction model for the slider body was also developed by Zhang and Bogy [2]. Since the MR element is very small compared to the slider body and its inside construction is also very complex, a 3-D heat transfer model for the slider body was later developed by Chen et. al[3]. But the heat transfer model they used for air bearing was the one developed by Zhang and Bogy [1]. Also, in [3] it was assumed that the non-air bearing surfaces of the slider were adiabatic. Since the heat convection to the surrounding air is about one hundred to one thousand times smaller than the heat flux in the air bearing, it was assumed that convection does not affect the MR temperature. However, at the trailing edge where the MR element is located, the heat conduction coefficient of the material is relatively small, and the MR element is very near the surrounding air, so the heat convection there is quite significant compared to heat conduction, and it cannot be neglected.

In this report we combine the 3-D heat transfer model for the slider body with a modified heat transfer model in the air bearing and boundary condition at the trailing edge. MR responses to different flying height and skew angles are calculated and some simulation results are compared with experimental data with good agreement. It is interesting to note that for the rail shape used in the experiments, when the flying height is very small (less than 60 nm), the electrical resistance of the MR element actually decreases with the flying height. This is contrary to the former belief that a larger flying height will cause less heat transfer in the air bearing and the MR temperature will rise. The phenomenon observed with very small flying heights is caused by a temperature jump at the air bearing and slider interface. This temperature jump is affected mainly by the local pressure. High pressure, which corresponds to higher molecule density, will cause more heat transfer. This non-intuitive MR temperature response (where MR temperature does not increase with increasing flying height) happens when two conditions obtain: 1) pressure and flying height do not tend to change together and 2) the pressure effect is large compared to the flying height effect. These two conditions occur together only at small flying heights.

A similar phenomenon is observed when we study the MR response to different skew angles. At small gap spacings (less than 60 nm), when the skew angle changes from –15 to 15 degrees, gap spacing and pressure change in different ways, causing a complex MR response.

The MR response with small flying heights is not the same for all sliders. The MR response simulation results of a tri-pad slider are also given in this report.

The agreement of simulation results with experimental results shows that the modified model works well. In the future the thermal model developed in this report may be applied to the thermal mapping of a disk surface [14], since accurate measurement of small flying heights is still difficult

2. 3-D Heat Transfer Model in the Slider

2.1 Governing equation

The governing equation for the 3-D unsteady heat conduction problem in the slider is:

$$r c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + S\,, \tag{1}$$

where r, c and k are, respectively, density, specific heat and thermal conductivity of the slider; T is the temperature difference between the slider plate and the ambient; t is the time; and x, y and z are coordinates in the slider. Because the slider is composed of different materials, the physical properties are not uniform. The source term S (unit: W/m^3) can be expressed as:

$$S = \begin{cases} Q_0 \quad (= \dfrac{I_s^2 R_s}{V_s}), & (x, y, z) \in \Gamma_s \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where, I_s, R_s, V_s and Γ_s are, respectively, bias current, electrical resistance, volume and the domain of the MR sensor.

2.2 Boundary conditions at non-air bearing surfaces

Air flows over the disk due to its rotation. Centrifugal force causes the air flow to have a radial and an axial component. The thickness of the boundary layer is given by White[3],

$$d = 5\sqrt{\frac{n}{w}} , \tag{3}$$

where *n* and *w* are the kinetic viscosity of the air and the disk rotation speed, respectively. The kinetic viscosity of air is 15.89e-6m^2/s, and when the disk rotation is 5400 rpm, *w* is about 550 rad/s. Therefore ***d*** is about 0.8 mm. Because the thickness of slider is about 0.4 mm, the slider is immersed in the boundary layer. We can use the boundary layer theory developed by Kays and Crawford[4] to determine the heat convection coefficient of the heat transfer between the surrounding air and the slider. In the boundary layer, the Nusselt number can be determined from the Reynolds number *Re* and the Prandtl number *Pr*:

$$N_u = \frac{h_{con} L}{k} \sim \sqrt{\mathrm{Re} \cdot \mathrm{Pr}} , \tag{4}$$

where h_{con}, *L* and *k* are the heat convection coefficient, the characteristic length of the disk and the heat conduction coefficient, respectively. At a radius of 40 mm with a disk rotation of 5400rpm, the velocity is about 20m/s. Therefore $\mathrm{Re} = \frac{uL}{n} \sim 10^5$. Under ambient temperature and pressure, the Prandtl number of air is 0.7, and the heat conduction coefficient *k* of air is 26.3e-3 W/m·K. From equation (4) we conclude that h_{con} is on the order of 100 W/m^2·K. The heat flux at these surfaces is:

$$q = h_{con}(T_s - T_0)$$

where T_s and T_o are temperatures of slider and environment, respectively.

2.3 Heat flux at the air bearing surface

At the air bearing-slider interface heat will be transferred from the slider to the disk through the air bearing cooling effect. This is a micro-structure quasi-steady heat transfer problem. Assuming the dimension in the z direction is much smaller than those in the x and y directions (x, y, z coordinates are plotted in Figure 1), we can write the energy equation as:

$$r_a C_{p_a} u \frac{\partial T}{\partial x} + r_a C_{p_a} u \frac{\partial T}{\partial y} - u \frac{\partial p}{\partial x} - u \frac{\partial p}{\partial y} = \frac{\partial}{\partial z}\left(k_a \frac{\partial T}{\partial z} \right) + m_a \left(\frac{\partial u}{\partial z} \right)^2 + m_a \left(\frac{\partial v}{\partial z} \right)^2 \qquad (5)$$

where r_a is the density, C_{pa} is the specific heat, k_a is the thermal conductivity, and T is the temperature of the air.

Zhang and Bogy [1] neglected all the terms on the left hand side of the above expression during the dimension analysis. They used a pressure gradient on the order of p_0/L, where p_0 is normal air pressure and L is the dimension of the slider, and reached the conclusion that $u\frac{\partial p}{\partial x} / m_a \left(\frac{\partial u}{\partial z} \right)^2$ is on the order of 10^{-3}. But in an air bearing, the pressure gradient is not very smooth. At some places the pressure gradient can be several orders higher than p_0/L. Therefore the third and fourth terms on the LHS in equation (5) cannot be neglected. The reduced energy equation is then written as:

$$- u \frac{\partial p}{\partial x} - u \frac{\partial p}{\partial y} = \frac{\partial}{\partial z}\left(k_a \frac{\partial T}{\partial z} \right) + m_a \left(\frac{\partial u}{\partial z} \right)^2 + m_a \left(\frac{\partial v}{\partial z} \right)^2, \qquad (6)$$

Let us assume that the disk has a non-zero velocity U in the x-direction and zero velocity V in the y-direction. If we apply the slip condition for the velocity and the jump condition for the temperature at the boundaries of the air bearing (introduced by Schaaf, et at. [5] and Kennard [6]), we can write the boundary conditions for velocity and temperature as:

$$u(0) = U + \frac{2 - s_M}{s_M}\, l\, \frac{\partial u}{\partial z}\Big|_{z=0}\,, \tag{7a}$$

$$u(h) = -\frac{2 - s_M}{s_M}\, l\, \frac{\partial u}{\partial z}\Big|_{z=h}\,, \tag{7b}$$

$$v(0) = \frac{2 - s_M}{s_M}\, l\, \frac{\partial v}{\partial z}\Big|_{z=0}\,, \tag{7c}$$

$$v(h) = -\frac{2 - s_M}{s_M}\, l\, \frac{\partial v}{\partial z}\Big|_{z=h}\,, \tag{7d}$$

$$T(0) = T_d + 2\,\frac{2 - s_T}{s_T}\,\frac{g}{g+1}\,\frac{l}{\mathrm{Pr}}\,\frac{\partial T}{\partial z}\Big|_{z=0}\,, \tag{7e}$$

$$T(0) = T_s - 2\,\frac{2 - s_T}{s_T}\,\frac{g}{g+1}\,\frac{l}{\mathrm{Pr}}\,\frac{\partial T}{\partial z}\Big|_{z=h}\,, \tag{7f}$$

where s_M is the momentum accommodation coefficient, s_T is the thermal accommodation coefficient, g_a is the ratio of specific heats at constant pressure and constant volume, l is mean-free-path of the air, and h is the air bearing spacing. We must note that the mean-free-path of air is a function of air pressure. According to Guthrie and Andrew[7], the relation between them is:

$$l = \frac{c}{p}\,, \tag{8}$$

where c is a constant and p is the pressure of air. Thus we can write the mean-free-path of air under any pressure as:

$$\ddot{e} = \frac{p_0}{p}\,\ddot{e}_0\,, \tag{9}$$

where l_0 is the mean-free-path under normal air pressure p_0 and its value is around 65 nm.

Introducing the velocity distribution obtained by other researchers [8,9]:

$$u = -\frac{1}{2m}\frac{\partial p}{\partial x}\left(a\,l\,h + hz - z^2\right) + U\left(1 - \frac{z + a\,l}{h + 2a\,l}\right), \tag{10a}$$

$$u = -\frac{1}{2m}\frac{\partial p}{\partial y}\left(a\,l\,h + hz - z^2\right), \tag{10b}$$

we obtain the heat transfer from the air bearing to the slider as follows:

$$q = -k_a \frac{T_s - T_d}{h + 2b\,l_0 \dfrac{p_0}{p}} - \frac{a\,l_0 p_0 h^2}{4pm_a}\left[\left(\frac{\partial p}{\partial x}\right)^2 + \left(\frac{\partial p}{\partial y}\right)^2\right] + \frac{m_a U^2 h}{2\left(h + 2a\,l_0 \dfrac{p_0}{p}\right)^2}$$

$$+ \frac{Uh\left[ah\,l_0 \dfrac{p_0}{p} + bh\,l_0 \dfrac{p_0}{p} + 2ab\left(l_0 \dfrac{p_0}{p}\right)^2\right]}{6\left(h + 2b\,l_0 \dfrac{p_0}{p}\right)\left(h + 2a\,l_0 \dfrac{p_0}{p}\right)}\frac{\partial p}{\partial x}, \tag{11}$$

where, $a=(2-s_M)/s_M$ and $b=2(2-s_T)g_a/s_T(g+1)Pr_a$. The first term of the right hand side is about 1-2 orders of magnitude larger than the other terms. This term represents the heat conduction. Since there is a temperature jump at the boundary, the effect of the heat conducted in an air bearing with a thickness of h is comparable to that of the heat conducted in a continuous material with the same thermal properties but of greater thickness, $h+2b\,l$. For a small h, comparable to $2b\,l$ (this often happens when flying height is smaller than 100 nm), the conduction term will not change monotonically with the flying height. It depends on other factors, such as pitch, roll and skew. When the flying height is large, h is the main factor affecting the heat flux in the air bearing, and hence also the MR temperature change.

3. Numerical and Experimental Methods

In order to determine the heat flux q from the slider to the air bearing, we must first find the pressure distribution p in the air bearing as required by equation (5). For a steady flying state the pressure distribution can be obtained by solving the Reynolds equation [10]. For an unsteady flying state, such as a slider flying over an asperity, the pressure distribution is obtained by dynamic slider air bearing analysis [11]. Since the heat transfer in the interface is quasi-steady [12], equation (11) can be used to calculate the heat flux at each transient flying state.

After the heat flux q is obtained, the coefficients for the integrated heat conduction equation can be determined for each grid point, and the temperature distribution in the slider can be solved for at each time step. The control volume method is applied to integrate the heat conduction equation (1). The alternating direction line sweep method and tri-diagonal matrix algorithm are applied to solve the matrix for the integrated equations.

We then determine the temperature variation and the MR signal change through several iterations. There is a linear relationship between the MR temperature rise DT and the electrical resistance change, obtained by Tian, et al [13] : $DT=DR/(aR_0)$, where R_0 and a are the initial resistance and the temperature coefficient of the MR sensor, respectively. The value of a is $0.00239K^{-1}$, and the expression for the MR voltage is: $V=I(R_0+ R_c+DR)$, where I is the bias current and R_c is the electrical resistance of coil which is around 5 ohm.

To measure changes in the MR stripe resistance, the MR read transducer of a commercial head-gimbal assembly was connected as one element of an electric resistor bridge. The bridge output voltage was amplified with a gain of 500-1000 to observe the result of resistance changes reported here. The change in MR resistance was calculated from the bridge output voltage. MR resistance and flying height were measured in situ while controlling skew and velocity using a Phase Metrics Dynamic Fly Height Tester.

4. Results and Discussions

Two kinds of sliders are used for analysis in this report, designated A and B.

4.1 Head A

The rail shape of head A is shown in Fig. 1. It's a 50% (2 mm ×1.6 mm) slider. The MR element is located at the outer trailing edge. Following are some results and discussions related to this head.

4.1.1 MR Resistance Change at Small Spacing

At small spacing, the heat transport in the air bearing will be significantly affected by the air pressure. As shown in the heat conduction term $-k_a \dfrac{T_s - T_d}{h + 2b\,l_0 \dfrac{p_0}{p}}$, higher pressure corresponds to more molecules per unit volume to transport energy, and thus has the effect of increasing the magnitude of the conduction term. So flying height and pressure will combine to determine the temperature change in the slider.

Figures 2(a), (b), and (c) show a comparison of simulation and experiments when the bias current in the MR sensor is 10mA, 12.5mA and 20mA respectively. Figure 2(d) shows gap spacing and pressure versus velocity. When velocity changes from 5m/s to

20m/s, the flying height at the MR stripe increases from 30 to 80 nm while the ratio of gap pressure to ambient pressure at the MR stripe changes from 0.5 to 3.5. When the flying height is less than 50 nm, the effect of increased pressure is more significant than the flying height effect, so the MR stripe is cooled and the resistance decreases. When the flying height is larger than 50 nm, the MR resistance increases with flying height since the pressure changes are less significant.

4.1.2 MR Signal Response at Larger Spacing

At larger spacing (more than about 80nm), the pressure effect is not as significant as the effect of flying height. Therefore, the MR temperature increases with increasing flying height. Figure 3 is the plot of MR resistance change versus flying height. The three curves are for pitch values of 95 μrad, 120 μrad, and 140 μrad respectively. It is shown that pitch angle doesn’t affect the MR response much. Experimental results for the device at such large spacings were not available.

4.1.3 MR Resistance Change versus Skew

Experimental data about MR resistance change versus skew angle were also obtained using Phase Metrics which can control the skew angle of the slider. The simulations were done under the same conditions. Figures 4(a) and (b) show comparisons of the simulation and the experiments with the slider at a radius of 37 mm and the bias current at 10 mA and 20 mA respectively. Figure 4(c) shows the gap spacing and gap pressure versus skew angle. When the skew angle changes from –15 to 15 degrees, the flying height first increases from 28 nm to 52nm, and then decreases to 30 nm, whereas the pressure first decreases, then increases, and then decreases again. Because the flying height is quite small (less than 60 nm), the pressure effect is significant. Comparing Figs. 4(a)-(c), we can see that the MR resistance change is just the inverse of the gap pressure. This is consistent with our explanation that increasing pressure causes more heat transfer in the air bearing, leading to decreasing MR temperature.

4.2 Head B

Head B is a 50% tri-pad slider. The rail shape is shown in Fig.5. The MR element is at the center trailing edge.

4.2.1 MR Response versus Velocity and Skew

Different sliders show different flying states, even at the same disk location and velocity, so their MR responses are different. For comparison, we simulated the MR response of the tri-pad slider. Figure 6(a) shows the MR resistance change versus velocity, and the related gap spacing and pressure over ambient pressure are plotted in Fig. 6(b). When velocity increases from 3m/s to about 22m/s, the gap spacing increases from 18nm to 128nm, and the normalized gap pressure drops from 0.9 to 0.6. Both the flying height effect and the pressure effect cause the MR temperature to rise. We can see that the MR resistance increases about 40 mOhm.

Figure 7(a) shows the MR resistance versus skew angle at the same radius and velocity used in Fig. 4. Figure 7(b) is the related gap spacing and pressure when skew angle changes from –15 to 15 degrees. Gap spacing and normalized gap pressure trends are inverse to each other. Therefore, they have the same effect on the MR temperature, and they cause an MR resistance change with the same trend as that caused by a change in gap spacing.

5. Conclusion

In this report we introduced a modified heat transfer model in the air bearing, combined with a 3-D heat transfer model in the slider body and a dynamic air bearing design model. Using this combined model, we studied the MR resistance dependence on the flying status of the slider. We can see that the MR read back signal is affected by the flying status of the slider in a complex way. Flying height, skew angle and varying rail shape each cause a different MR response. However it appears that pitch and roll do not have much impact on the MR signal.

We observed that increasing flying height would not always lead to increasing MR temperature. At a very small flying height (within about 100nm), for certain kinds of sliders, the MR temperature can decrease with increasing flying height. This is caused by a significant pressure effect on the heat transfer in the air bearing. When the flying height is large enough (greater than 80nm), it overrides the pressure effect and causes a temperature change along the same trend as the flying height. This is the situation that is observed normally.

When the skew angle is changed with disk speed held constant, the MR resistance changes due to the combined effects of flying height and pressure. For the two sliders we studied pressure seems to be the dominant parameter, since the variation of the MR resistance is inverted with respect to the variation of gap air bearing pressure. That is, we observe that higher pressure causes more efficient heat transfer and consequently lower MR temperature.

We compared some simulation results with experimental data. The agreement between them shows that the thermal model introduced in this report works well.

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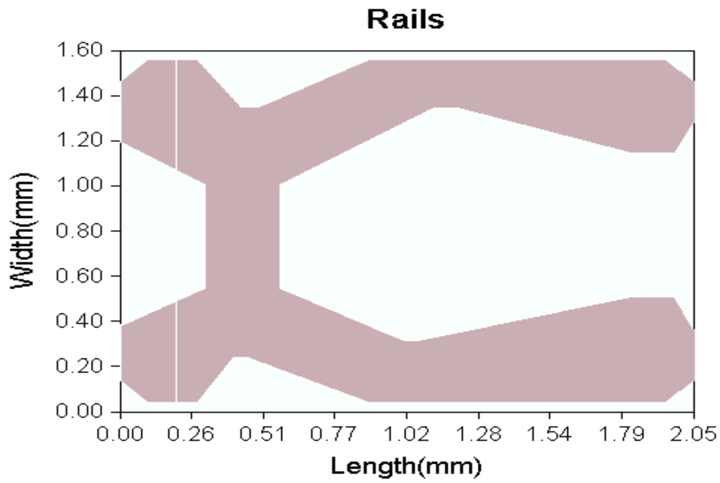


Fig. 1 Rail Shape

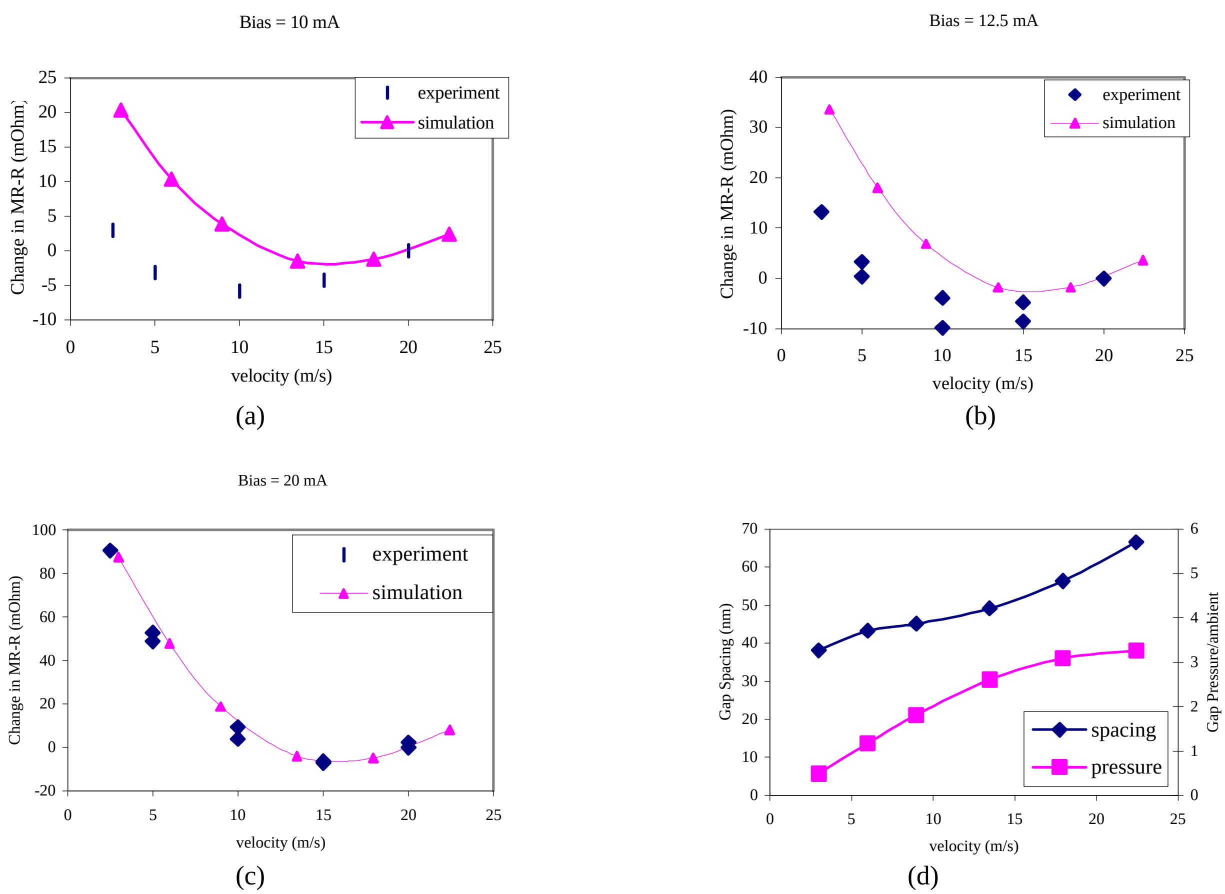


Fig. 2 MR-R response versus velocity (a), (b),(c), and related gap spacing and pressure (d).

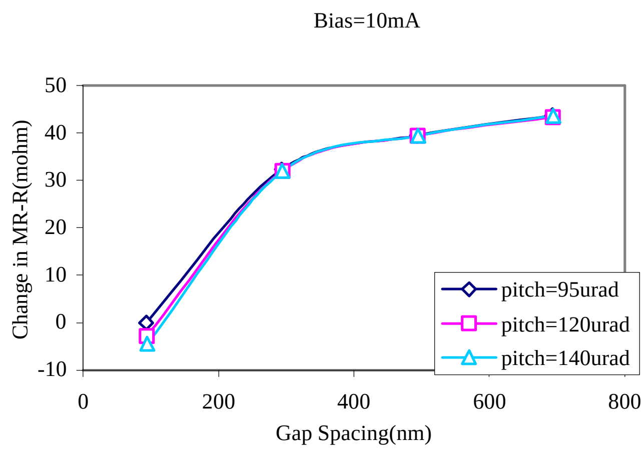


Fig. 3 MR resistance change at greater flying height for different pitches

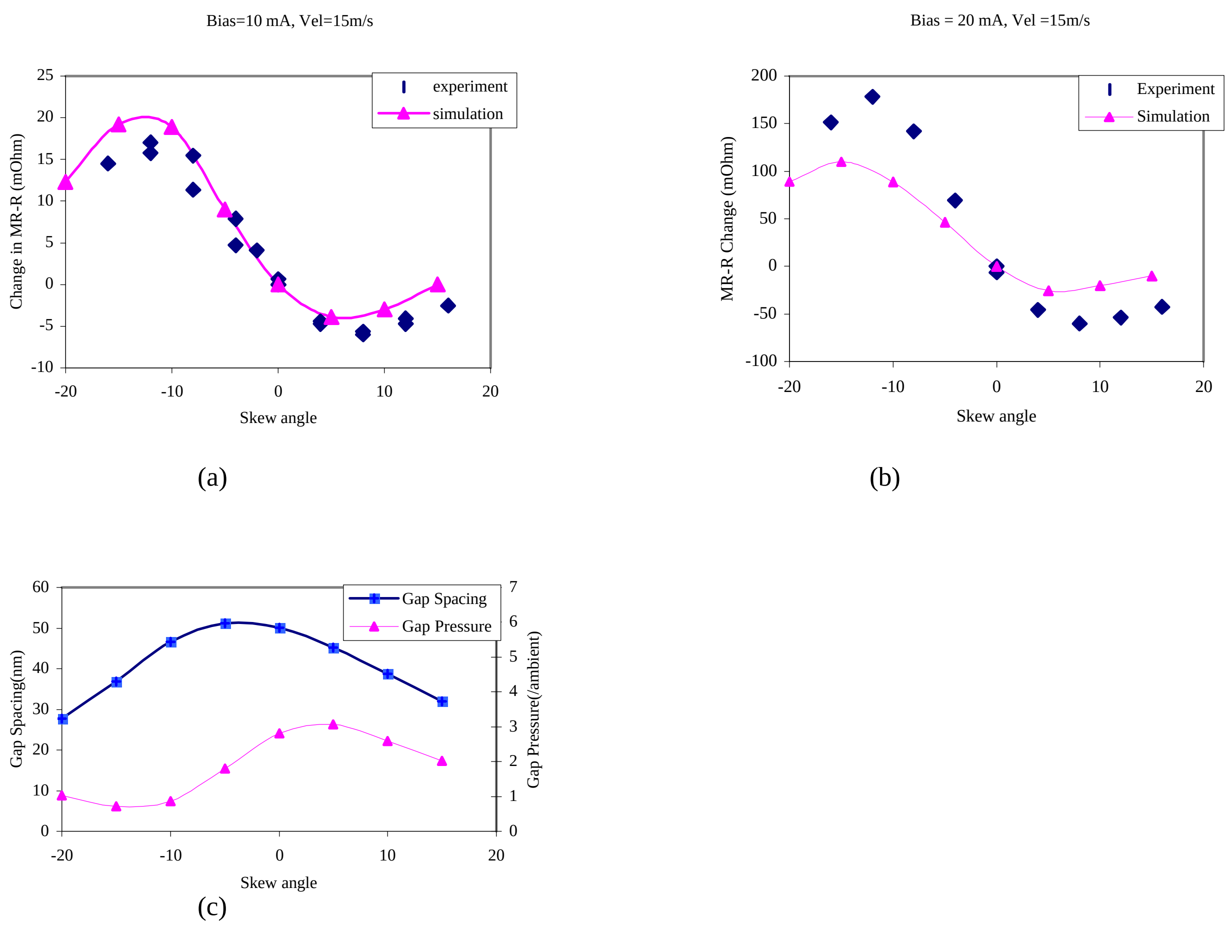


Fig. 4 MR resistance change versus skew angle (a), (b) and related gap spacing and pressure (c)

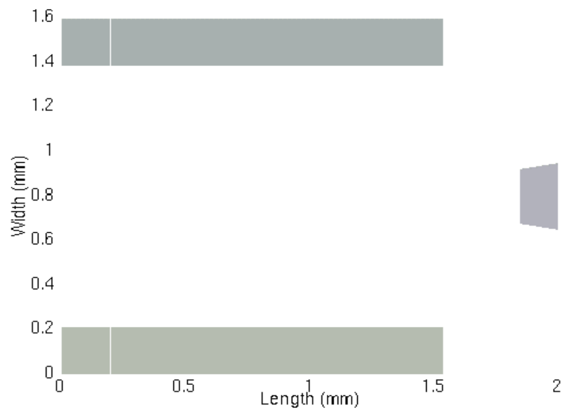
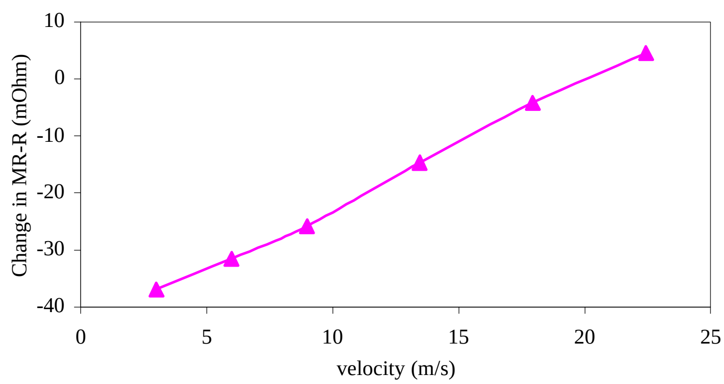
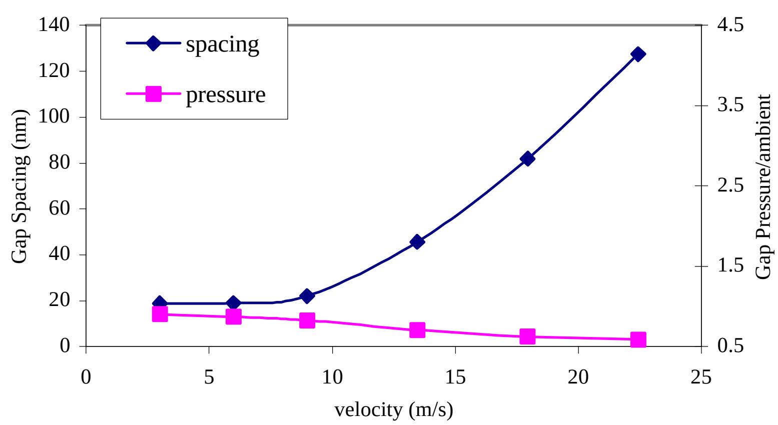


Fig. 5 Rail shape of a tri-pad slider

Bias = 12.5 mA at Radius 23.8mm

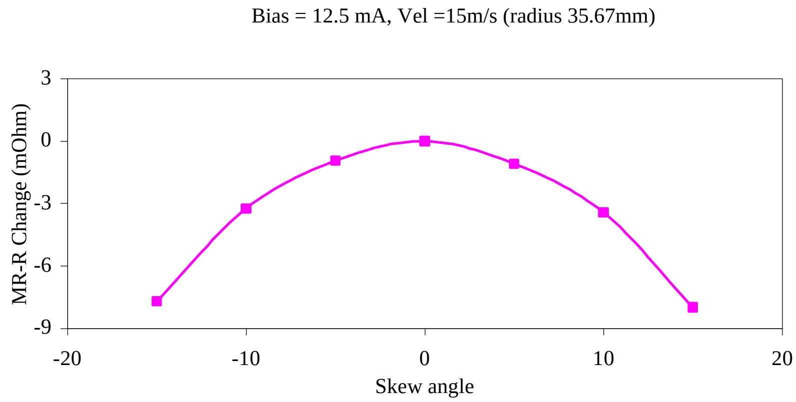


(a)

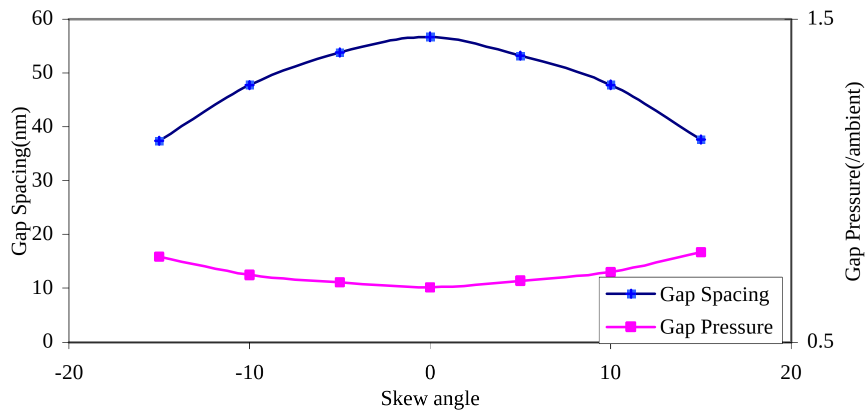


(b)

Fig. 6 MR resistance change versus velocity at small spacing (a) , and related gap spacing and pressure (b).



(a)



(b)

Fig. 7 MR resistance change versus skew angle (a), and related gap spacing and pressure (b)