TEMERATURE RESPONSE OF A MR HEAD WHEN IT FLIES OVER AN ASPERITY

Shuyu Zhang and David B. Bogy

Computer Mechanics Laboratory, University of California, Berkeley, CA 94720

ABSTRACT

A 2-D model is developed for the heat transfer in a MR head in this report. Using this model, the MR temperature response is studied for various cases. It is found that the temperature distribution in the head depends on the current through it and is only significant within a small area around the MR transducer at the trailing edge. With a typical current value (say 10 *mA*), the MR temperature is about 25 °C higher than that of the ambient. When the slider flies over an asperity without contact, the MR temperature fluctuates following the fluctuation of the air bearing spacing, which is caused by the cooling effect of the air bearing. The resulting MR temperature variation is about 0.06 °C, which may cause the MR readbach signal to change by about 3%.

Key words: magnetic recording, MR head, air bearing, thermal asperity.

1. Introduction

The magnetoresistive (MR) head was developed (Hunt, 1971) using the principle that the resistance varies with the variation of the magnetization in the MR sensor. A problem with the MR head is that it is very sensitive to the temperature because the resistance is also temperature dependent. One such phenomenon is that the MR readback signal fluctuates with the fluctuation of the flying height when the slider flies over an asperity without contact (Tian, et al., 1997), which was said to be caused by the fluctuation of the heat transfer in the air bearing. It was concluded that the air bearing acted as a coolant.

Tian, et al, (1997) and Zhang and Bogy (1997a) estimated the temperature variation of the MR sensor using a simple lumped-heat-capacity method, in which the temperature was assumed to be uniform in the sensor. A diagram describing the simplified model they used is shown in Fig. 1(a), where heat Q_0 is generated in the MR sensor due to the current through it and is balanced by the heat transferred to the air bearing. In this report, we modify this lumped-heat-capacity model to a 2-D heat conduction model. We first assume that the MR sensor, together with its shields, provides the heat source with uniform heat generation Q_0. For convenience, we call this heat source package the MR head in the following analysis. Then, we assume that the MR head is inlaid in a large thin plate, say the plate like a rail at the trailing edge of a tri-pad slider, as shown in Fig. 1(b). We call it the "slider plate" for the convenience. The heat Q_0 is transferred to the other part of the slider plate as well as the air bearing, and a temperature field is distributed within the plate. Since the slider plate is large and thin, we can treat the heat transfer in it as a 2-D problem approximately.

Strictly speaking, to calculate the temperature in a MR sensor, we need to consider the heat transfer in a slider as a whole, which is usually a 3-D problem, not only because its thickness dimension is comparable to its length and width dimensions, but also because it has an irregular air bearing surface. But as a first step, we focus our work on illustrating the analytical method. Therefore, a 2-D analysis is a convenient and acceptable approach. We will see later that several interesting results can be obtained from this 2-D analysis, which are very helpful in understanding the mechanism of the "cooling" effect of the air bearing.

As in our previous work (Zhang and Bogy, 1997a and 1997b), we assume that all the physical properties are uniform in the air bearing due to the small temperature change and the low Mach number.

2. Heat Transfer Model in a Slider Plate

For a 2-D heat conduction problem in a slider plate, we can write the governing equation as follows:

$$\rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) + S \,, \qquad (1)$$

where ρ, c_p and k are, respectively, density, specific heat and thermal conductivity of the slider plate, T is the temperature, τ is the time, and x and y are coordinates in the slider plate. Note that the slider plate is composed of different materials, so the physical properties are not uniform throughout it. The source term S (unit: W/m^3) consists of the heat generation Q_0 in the MR head and the heat exchange q with the air bearing. The heat exchange between the slider plate's top side and the air is negligible. Thus, S can be expressed as:

$$S = Q_0 + \frac{q}{t} \tag{2}$$

where t is the thickness of the slider plate. The heat generation Q_0 can be expressed as:

$$Q_0 = \begin{cases} \dfrac{I_s^2 R_s}{A_s t} & (x, y) \in \Gamma_s \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where, I_s, R_s, A_s and Γ_s are, respectively, current, resistance, area and domain of the MR head, and t is the thickness of the slider plate.

The heat flux between the slider plate and air bearing was studied by Zhang and Bogy (1997a, b) for both steady and unsteady cases, and it can be expressed as follows:

$$q = -k_a \frac{T - T_d}{h + 2b\lambda_a} + \frac{h^3}{24\mu_a}\left[\left(\frac{\partial p}{\partial \xi}\right)^2 + \left(\frac{\partial p}{\partial \eta}\right)^2\right] + \frac{\mu_a U^2 h}{2(h + 2a\lambda_a)^2} - \frac{Uh^3}{6(h + 2b\lambda_a)(h + 2a\lambda_a)}\frac{\partial p}{\partial \xi}, \tag{4}$$

where, ξ and η are coordinates in the air bearing, k_a, μ_a and λ_a are, respectively, the thermal conductivity, viscosity and mean-free-path of the air, T_d is the temperature of the disk surface, U is the linear velocity of the disk, h is the air bearing spacing, $a=(2-\sigma_M)/\sigma_M$ and $b=2(2-\sigma_T)\gamma_a/\sigma_T(\gamma+1)Pr_a$, where σ_M is the momentum accommodation coefficient and σ_T is the thermal accommodation coefficient, γ_a is the ratio of specific heats at constant pressure and constant volume, and Pr_a is the Prandtl number of the air. Clearly, S is not uniform and is a function of position.

Since the slider plate has very small thickness t and its heat exchange with the environment by convection and radiation is negligible, the boundary condition can be regarded as adiabatic around its edges.

3. Integration of the Conduction Equation

We use Patankar's (1980) control volume method to integrate the conduction equation (1). A 2-D control volume is depicted in Fig. 2, where the shaded area is the control volume, and Δx and Δy are lengths of its two edges. The capital letters E, S, W, N and P represent the grid nodes and small letters e, s, w and n represent the related control volume surfaces. For the convenience of analysis, we re-define the variable T as the temperature difference between the slider and ambient. All of the equations mentioned above remain unchanged except that $T-T_d$ is replaced by T in equation (4), where we assume the disk surface has the same temperature as the environment. We can also write equation (4) in a simpler form as: $q=-A\cdot T+B$, where A is the coefficient of the 1st term and B is the rest of the terms on RHS.

Now integrating equation (1) over the control volume, we get:

$$\int_{\tau}^{\tau+\Delta\tau}\int_{s}^{n}\int_{w}^{e}\rho c_p\frac{\partial T}{\partial\tau}dxdyd\tau=\int_{\tau}^{\tau+\Delta\tau}\int_{s}^{n}\int_{w}^{e}\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dxdyd\tau+$$
$$\int_{\tau}^{\tau+\Delta\tau}\int_{s}^{n}\int_{w}^{e}\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)dxdyd\tau+\int_{\tau}^{\tau+\Delta\tau}\int_{s}^{n}\int_{w}^{e}Sdxdyd\tau\,. \qquad (5)$$

Substituting q into (5), expanding and re-arranging it yields:

$$a_PT_P=a_ET_E+a_WT_W+a_NT_N+a_ST_S+a_{P0}T_{P0}+b\,. \qquad (6)$$

Equation (6) is in an implicit form and T_{P0} represents the temperature values at the last iteration. The related coefficients are:

$$a_P = a_E + a_W + a_S + a_N + a_{P0} + S_P \Delta x \Delta y \, , \tag{7-a}$$

$$a_E = k_e \frac{\Delta y}{(\delta x)_e} \, , \tag{7-b}$$

$$a_W = k_w \frac{\Delta y}{(\delta x)_w} \, , \tag{7-c}$$

$$a_N = k_n \frac{\Delta x}{(\delta y)_n} \, , \tag{7-d}$$

$$a_S = k_s \frac{\Delta x}{(\delta y)_s} \, , \tag{7-e}$$

$$a_{P0} = \frac{\rho c_p \Delta x \Delta y}{\Delta \tau} \, , \tag{7-f}$$

$$b = S_C \Delta x \Delta y \, , \tag{7-g}$$

where, $S_P=A/t$ and $S_C=Q_0+B/t$, and k_e, k_w, k_n and k_s are, respectively, the thermal conductivity at each edge of the control volume.

Equations (6)~(7) are written for the inner control volumes. A similar method can be used for the boundary control volumes. The detailed derivation will not be presented here.

4. Numerical Approaches

The unsteady problem described above arises either from a sudden input of a current into the MR sensor, or from unsteady heat flux from the air bearing to the slider plate, which is caused by the unsteady flying of the slider, or from both of them. To solve this problem, a prerequisite is to know the pressure distribution *p* in a SDI (see equation (4)). For a steady flying state, the pressure distribution can be obtained by solving the Reynolds equation (Lu, and Bogy , 1997). But for an unsteady flying state such as a slider flying over an asperity, the calculation is more complicated. Zhang and Bogy (1997a) studied the heat transfer in a SDI and concluded that it was quasi-steady. Therefore, equation (4) is still valid for calculating the heat flux at each transient flying state obtained by using a dynamic slider air bearing analysis (Hu and Bogy, 1995 and 1996).

After the heat flux *q* is obtained, the coefficients in equation (6) can be determined for each grid, and the temperature distribution in the MR head can be solved for each time step. To solve the matrix from equation (6), we use the Gauss-Seidel method in this report. There are also many other efficient solvers, such as ADI, multi-grid control volume methods, etc.; they will be discussed in future work.

5. Simulation Results

We choose a 50% tri-pad slider in the following analysis. This slider has taper angle and length of 0.01 *rad* and 0.2 *mm*, respectively, and a recess depth of 3 μm. It flies at the position of 23 mm away from the center of the disk while the disk rotates at 6400 rpm. Its rail shape is shown in Fig. 3(a), in which the rail at the trailing edge is square. The reason to choose this square end rail is for the convenience of dealing with the finite difference grids. So we do not need to consider using the non-rectangular grids on the rail edges. The pressure profile of the steady flying state is solved using the CML Air Bearing

Design Code (Lu and Bogy , 1995), shown in Fig. 3(b), and the flying characteristics are shown in Table 1.

Table 1. Flying characteristics of the tri-pad slider (Fig. 3(a))

Position r (mm)	Skew (degree)	Pitch (μ rad)	Roll (μ rad)	FH-CTE[✞] (nm)
23	0.0°	175.4	8.0	45.0

✞Flying height at the central trailing edge

5.1 MR Temperature Response for a Slider in Steady State

We assume that the slider is in a steady flying state at the beginning. A current is supplied to the MR sensor which generates heat according to Joule's law. If the current is 10 mA and the resistance of the MR sensor is 20 Ω, then the heat generation of the MR head (with size of $20\mu m \times 20\mu m \times 3\mu m$) is about 1.7×10^{12} W/m^3. With this heat generation, the temperature in the slider plate is re-distributed and become higher than the ambient temperature, which causes heat to be transferred into the air bearing. A steady temperature distribution is finally reached by balancing the heat generation and heat exchange between the slider plate and air bearing. The transient temperature distribution can be obtained by solving the model presented in sections 3.

Figure 4 shows the simulation results of the MR temperature response. Figure 4(a) is the average MR temperature versus time, where temperature is averaged over the whole MR head. It is seen that as time elapses, the MR temperature gradually reaches a steady value, which is about 25 °C higher than that of ambient.

The temperature distributions of the slider plate are shown, respectively, in Figs. 4(b)~(d) for three different times. Clearly, the temperature increases with time, but the significant temperature variation is restricted in a small area at the trailing edge. It suggests that we can focus on a small area, say an area covering only the rail surface at the tailing edge, to study the MR temperature response with reasonable precision and less computation time.

5.2 MR Temperature Response for the Slider Flying Over An Asperity

We previously studied the variation of the heat flux between the slider and the air bearing when the slider flies over an asperity without contact (Zhang and Bogy, 1997a). In that paper we concluded that the heat flux varies inversely with the air bearing spacing. That is, when the slider flies closer to the disk surface, more heat will be transferred out of it. This is the so-called “cooling” effect of the air bearing. Using a simple assumption that the temperature is uniform in the MR head and its variation is caused by the maximum heat flux change between the slider and air bearing, we estimated that the MR temperature changed by 0.1 °C, which in turn was estimated to cause the MR readback signal to change by 5%. The actual process of the MR temperature response is far more complicated than this. For example, when the air bearing spacing fluctuates, the heat flux between the slider and air bearing changes, and thus the MR temperature changes simultaneously, which in turn causes an additional change of the heat flux between the slider and air bearing. Therefore, an unsteady heat transfer model is needed to simulate the MR temperature directly.

In this section, we use the 2-D model presented in Section 2 to study the MR temperature response as the slider flies over a rectangular asperity. For convenience, we choose the same tri-pad slider and conditions used in the last case. Since the steady state flying height is 45 *nm* (Table 1), we choose the asperity height to be 40 *nm* with length and width of 150μm and 300μm. The simulation results are shown in Fig. 5.

We know that the heat flux between the MR head and the air bearing, which affects the temperature distribution in the MR head, is closely related to the air bearing spacing. To compare their relationship, we plot the average temperature over the MR head and the air bearing spacing of a single point 5 μm away from the central trailing edge (CTE) in the same figure (Fig. 5). Note that the average MR temperature is actually affected by the heat transfer in a local area around the MR head instead of only by the heat transfer at a single point. But this single point air bearing spacing still can be used to analyze qualitatively the overall effect of the heat transfer of the air bearing on the MR temperature.

Looking at Fig. 5, we find that there exist two zones concerned with the effect of the asperity. We call them the "major asperity influence zone (MAIZ)", which is related to the period for the asperity to enter and leave the air bearing of the end rail, and the "vibration influence zone (VIZ)", which is related to the short periods before the asperity reaches and after it leaves the air bearing of the end rail. Since the air bearing spacing under the MR head decreases sharply in the MAIZ due to the geometry of the asperity, the MR temperature also decreases sharply because of the cooling effect of the air bearing. While in the VIZ, the air bearing spacing is mainly affected by the vibration of the slider, so the MR temperature reaches its local peaks and bottoms following the fluctuation of the air bearing spacing and gradually damps to its steady state value. It should be pointed out that the vibration effect remains in the MAIZ, although it is smaller than that of the direct involvement of the asperity in this case. Therefore, we still observe the local peaks and bottoms in the MAIZ.

Besides the high frequency fluctuation of the MR temperature, there exists also a low frequency fluctuation of the MR temperature (Fig. 5), which is concerned with the low frequency fluctuation of the air bearing spacing. To illustrate this phenomenon, we choose two time intervals and amplify the related air bearing spacing, and compare them with the MR temperature (Fig. 6). Clearly, this low frequency fluctuation of the air bearing causes the related low frequency fluctuation of the MR temperature.

From Fig. 5, we see that the maximum MR temperature variation is about 0.06 °C, which agrees closely with the result of 0.1 °C reported in Zhang and Bogy’s (1997a) work based on dimensional analysis. This temperature variation is estimated to cause the MR readbach signal to change by about 3%.

6. Conclusion

The MR readback signal is very sensitive to the temperature, which may be affected by the fluctuation of the heat transfer in the air bearing. In this report, we develop an unsteady 2-D heat conduction model to study the MR temperature response related to the various thermal disturbances. A basic assumption for this 2-D model is that the MR temperature variation is only significant within a small area around the MR head. Therefore, we can study a 2-D heat conduction problem by focusing on a small air bearing surface with reasonable precision. Other assumptions include uniform physical properties and quasi-steady heat transfer in the air bearing, which have been mentioned in our previous works (Zhang and Bogy, 1997a, b).

Using this model, we studied two cases of the MR temperature response related to a sudden current supply but with a steady flying state and a slider flying over an asperity without contact. The simulation result of the former case shows that the temperature difference (related to the ambient temperature) is only significant within a small area at the trailing edge, which is identical to the basic assumption we used in developing the 2-D model. Also, the MR temperature is about 25 °C above ambient when the system reaches the thermal steady state.

The simulation results of the latter case show that the MR temperature response has a sharp decrease at first and then damps to its steady state value when the slider flies over an asperity without contact, which is caused by the cooling effect of the air bearing. With the given MR current and resistance as well as the size of the asperity, the maximum MR temperature variation is about 0.06 °C, which may cause the MR readbach signal to change by about 3%.

Strictly speaking, the heat conduction in a MR head is a 3-D problem. Since the heat is also transferred in the *z* direction instead of being restricted in a thin plate, the 2-D model may over estimate the MR temperature. But as a method of studying the mechanism of the thermal asperity, the 2-D model provides a simple approach and gives reasonable results. A 3-D model can be realized based on the 2-D model by considering the conduction in the *z* direction and arbitrary rail shapes. The computation time will be an important issue and efficient numerical methods need to be investigated. In addition, a MR head can be regarded as composed of different materials related to shields and sensor, and a micro-structural treatment needs to be considered in the analysis because of the small size of the MR sensor.

References

Hu, Y., Bogy, D. B., 1995, “The CML Air Bearing Dynamic Simulator”, *CML Tech. Report*, No 95-011, UC Berkeley.

Hu, Y., Bogy, D. B., 1997, “Dynamic Stability and Spacing Modulation of Sub-25 nm Fly Height Sliders”, *ASME Journal of Tribology*, Vol.119, pp646-652.

Hunt, A. P., 1971, “A Magnetoresistive Readout Transducer”, *IEEE Transactions on Magnetics*, Vol. Mag-7, No. 1, pp.150-154.

Lu, S., Bogy, D. B., 1995, “CML Air Bearing Design Program User’s Manual”, *CML report*, No. 95-003, UC Berkeley.

Lu, S., 1997, *Numerical Simulation of Slider Air Bearing*, Doctoral Dissertation, Department of Mechanical Engineering, University of California, Berkeley.

Patankar, S. V., 1980, *Numerical Heat Transfer and Fluid Flow*, McGray-Hill, New York.

Tian, H., Cheung, C-Y., Wang, P-K., 1997, “Non-Contact Induced Thermal Disturbance of MR Head Signals”, *IEEE Transactions on Magnetics*, Vol.33, No.5, pp3130-3132.

Zhang, S., Bogy, D. B., 1997a, “Variation of the Heat Flux between a Slider and the Air Bearing when the Slider Flies over an Asperity”, presented in the *INTERMAG98*, and will appear in *IEEE Transactions on Magnetics*.

Zhang, S., Bogy, D. B., 1997b, “A Heat Transfer Model for Thermal Fluctuation in an Ultra-Thin Air Bearing”, submitted to the *International Journal of Heat and Mass Transfer*.

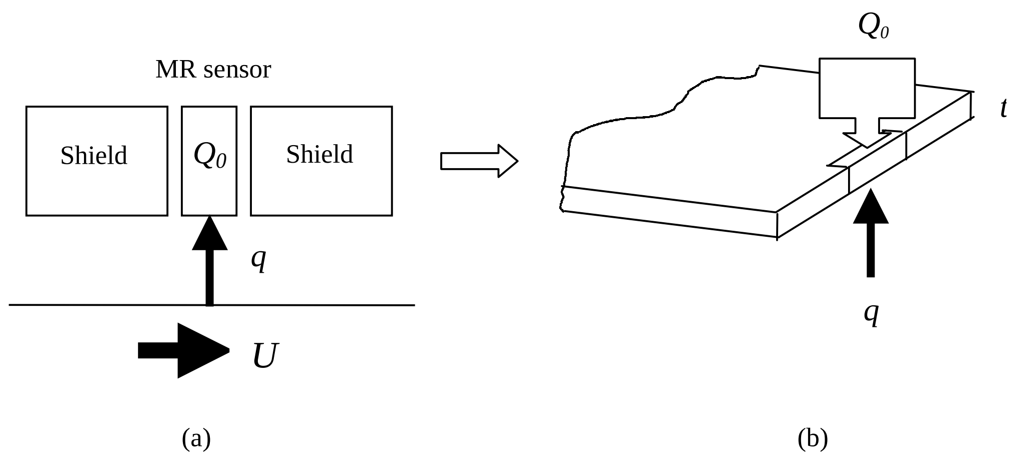


Fig. 1 Diagram for the 2-D heat transfer model

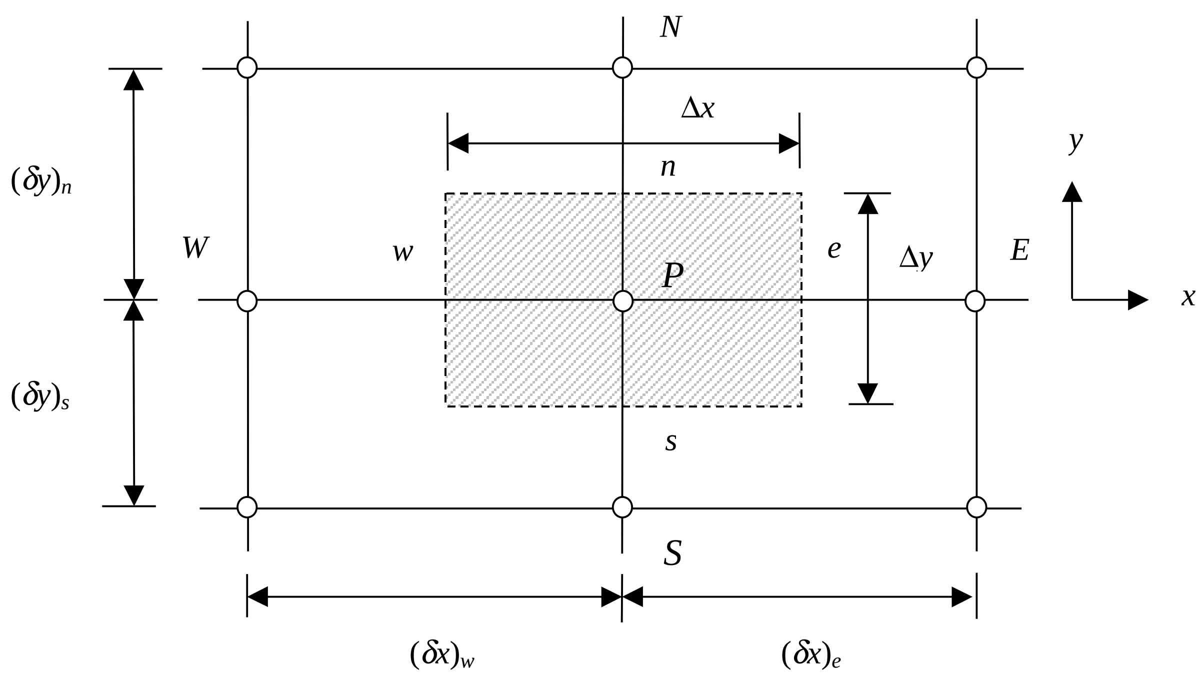
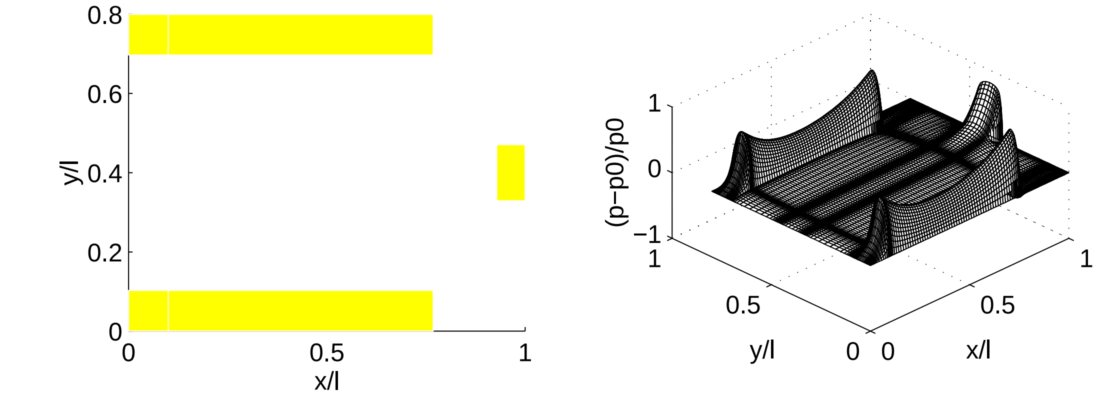
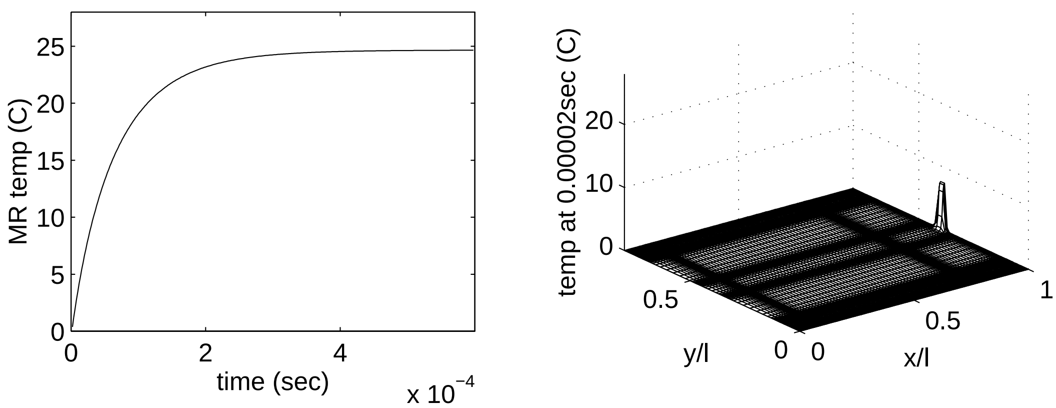


Fig. 2 Diagram of the control volume

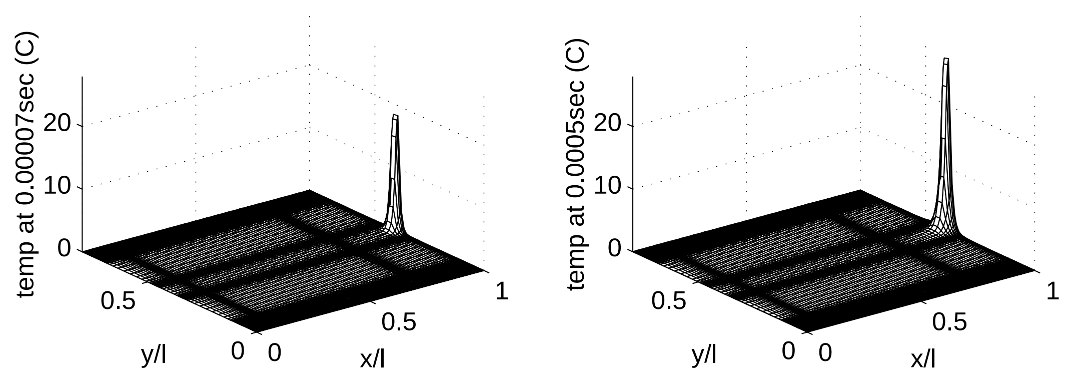


(a) (b)

Fig. 3 Rail shape (a) and pressure profile (b) of a tri-pad slider studied



(a) (b)



(c) (d)

Fig. 4 MR temperature response when a current supplied to the MR transducer: (a) MR temperature response vs. time; (b)~(d) temperature distribution at 3 times

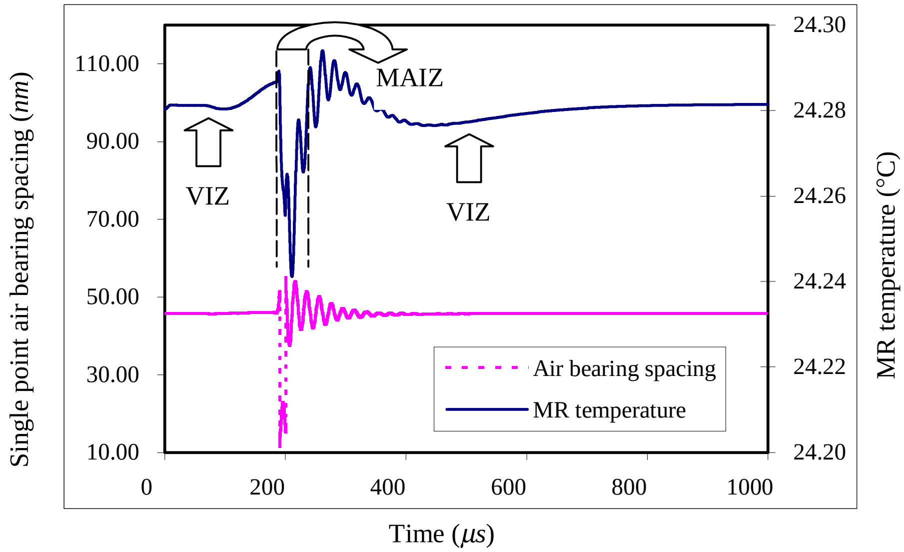


Fig. 5 MR temperature response when the slider flies over an asperity without contact

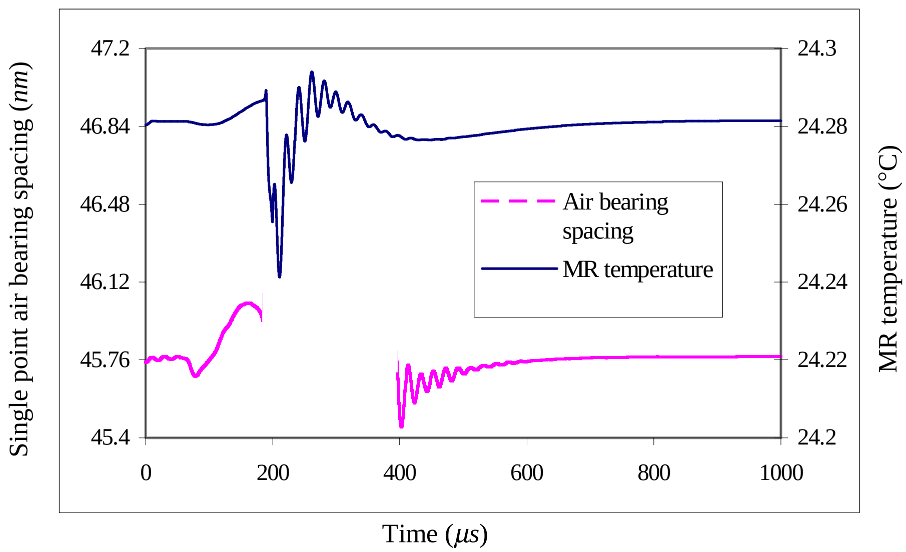


Fig. 6 MR temperature response when the slider flies over an asperity without contact: low frequency effect