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Predicting the Flying Performance of Thermal Flying-Height Control Sliders in Hard Disk Drives

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Abstract

Thermal flying-height control (TFC) sliders have been recently used in commercial hard disk drives (HDDs) to increase the HDDs' capacity. The design of this new class of sliders depends on the numerical prediction of their flying performance, which requires a model for heat flux on the surface of the slider facing the disk. The currently widely used heat flux model is based on a first order slip theory and is believed to lack sufficient accuracy due to its limitation of applicability. This paper implements a more accurate heat flux model and compares some numerical results based on these two models. It is found that the numerical results based on the current model have a relative error less than 10% for state-of-art sliders for which a pressure peak appears near the transducer. It is suggested that numerical prediction based on the current model for some kinds of sliders, however, for which no pressure peak appears near the transducer might cause larger errors.

Hard disk drives (HDDs) use magnetic disks, which rotate up to 15,000 rounds per minute (RPM) and produce linear speeds on the order of 10 m/s, to store information. The data on the disk is read and written by a read-write transducer embedded in a slider that flies over the disk. The disk's rotation drags air into the region between the slider and the disk, known as the head-disk interface (HDI). Due to compressibility and rarefaction of the air in the HDI, a lift force on the slider is produced by the air pressure on the slider's surface facing the disk, known as the air bearing surface (ABS). This lift force keeps the slider flying at some distance away from the disk. By carefully designing the pattern on the ABS, the pressure distribution on the slider can be adjusted so that the slider flies over the disk stably with a required separation as the disk rotates, which increases the HDDs' reliability. The HDDs' capacity is inversely related to the slider's flying height (FH) at the read-write transducer [1]. One approach, which has recently been employed in the HDD industry to increase the HDDs' capacity, is to use the thermal flying-height control (TFC) slider to reduce the FH at the transducer [2]. For a TFC slider, a heating element is embedded in the slider and located near the transducer, as shown in Fig. 1. When power is supplied to the heating element, the temperature around the transducer changes and, due to thermomechanical coupling, the slider protrudes locally near the transducer, which decreases the distance of the transducer from the disk [2] [3] [4].

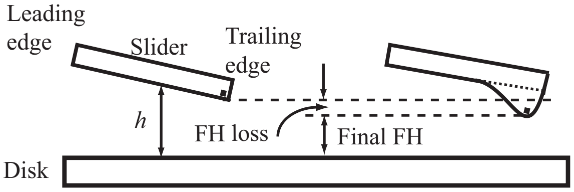

FIG. 1: The deformation of a thermal flying-height control (TFC) slider. The black square near the trailing edge is the read-write transducer used to read data from and write data onto the disk. When power is supplied to the heating element, which is near the transducer but not shown in the figure, the slider deforms locally near the transducer and the air gap thickness underneath the transducer decreases. The flying height (FH) loss refers to the difference between the initial flying height at the transducer of the undeformed slider and the final flying height at the transducer of the deformed slider. Since the pressure distribution changes with the ABS profile, the slider's deformation also induces changes in its pitch and roll compared to its undeformed state.

To assist in the design of this new class of sliders, numerical prediction of the sliders' performance is needed and it requires a heat flux model in the air bearing, which serves as boundary conditions for the calculation of the slider's deformation. The current model for the heat flux considers heat conduction as the dominant contribution and is derived from the first order slip theory [5] [6] [7]. In view of the fact that the air gap thickness, h, in the HDI varies over the slider from several nanometers to around 1 micrometer and the mean free path of air molecules outside the HDI is around 65nm, the Knudsen number $\mathrm{Kn} = \lambda/h$, where λ is the local mean free path of air in the HDI, might not be very small. Since the first order slip theory, in principle, only applies to a slightly rarefied gas for which $\mathrm{Kn} < 0.1$, it is not guaranteed that the current heat flux model applies to the entire HDI. Chen et al. [8] found that the heat flux predicted by the first order slip theory differs from widely accepted data by about 10% when the Knudsen number is larger than 10. Since calculating the TFC sliders' deformation is a nonlinear program, it is unknown a priori how much of this 10% error in the heat flux calculation of the current model causes, and there is concern about the accuracy of numerical predictions based on the current model. Chen et al. [8] proposed a new phenomenological model introducing the effect of the presence of the slider and the disk on the mean free path. Similar ideas have also been used to improve the calculation of mass flow rate in Poiseuille flow of a rarefied gas, among others [9]. Chen et al.'s model compares better with experiments and other widely accepted data, especially when the Knudsen number is higher than 0.1. This paper incorporates Chen et al's more accurate model and compares the numerical predictions of the two models.

According to the first order slip theory, the heat conduction on the ABS is [5] [6]

$$q = -k \frac{T_s - T_d}{h + 2\frac{2-\sigma_T}{\sigma_T}\frac{2\gamma}{\gamma+1}\frac{1}{\mathrm{Pr}}\lambda} \tag{1}$$

where k is the thermal conductivity of the air, T_s is the slider's temperature, T_d is the disk's temperature, h is the local flying height of the slider, σ_T is the thermal accommodation coefficient, γ is the heat capacity ratio of the air, λ is the local mean free path of the air, $\mathrm{Pr} = \nu/\alpha$ is the Prandtl number of the air, ν is kinetic viscosity of the air and α is thermal diffusivity of the air.

The current heat flux model, Eq. (1), only considers the effect of local pressure on the mean free path, and neglects the effect of the presence of the slider and the disk. Since the mean free path is the average distance traveled by molecules between two consecutive collisions, when the distance between the two boundaries is less than the usual mean free path, the free distance molecules can travel will be affected by the boundaries, and the collision of air molecules with boundaries needs to be considered in the calculation of the mean free path of air molecules moving in the HDI [8] [9] [10]. Along this line, Chen et al. [8] proposed the following modified mean free path:

$$\lambda_m = \begin{cases} \lambda\left(1 - \frac{1}{4}\frac{\lambda}{h}\right), & h \geq \lambda \\ \lambda\left(\frac{3}{4}\frac{h}{\lambda} - \frac{h}{2\lambda}\ln\left(\frac{h}{\lambda}\right)\right), & h < \lambda \end{cases} \tag{2}$$

where $\lambda = \lambda_0 p_0/p$ is the mean free path of the air, λ_0 is the mean free path of the air outside the HDI, p is the local pressure in the HDI and p_0 is the ambient pressure outside the HDI. Chen et al.'s phenomenological heat flux model replaces λ in Eq. (1) by the modified mean free path λ_m in Eq. (2).

The calculation of a TFC sliders' flying performance involves modeling the complex structure of the heating element and the read-write transducer and calculating the slider's deformation based on its thermoelastic properties, for which iterative approaches have been used and proven to be effective [3] [4] [11]. This approach iterates between two steps: in the first step, the air flow field and the air pressure distribution in the HDI are calculated by using the finite volume method (FVM) to solve the generalized Reynolds equation, which is derived from the linearized Boltzmann equation and applies to the whole HDI [12]; in the second step, the slider's deformation and the deformed ABS profile are calculated using a commercial finite element solver ANSYS with detailed models of the heating element and read-write transducer [11].

Figure 2 shows the air pressure distribution on a commercial TFC slider's ABS. A pressure peak appears near the transducer, which makes the air flow underneath the transducer act as a spring with a high stiffness to stabilize the slider as it moves on the disk. This pressure peak decreases the local mean free path and local Knudsen number since the mean free path is inversely proportional to the local pressure.

Figure 3 shows a comparison of the reduction in the slider's flying height at the transducer resulting from the slider's thermal deformation. Both of the numerical results compare well with experiments, but the one based on Chen et al.'s model shows slightly less difference from the experiments. The maximum difference between the two predictions is around 0.1nm as seen from the inset.

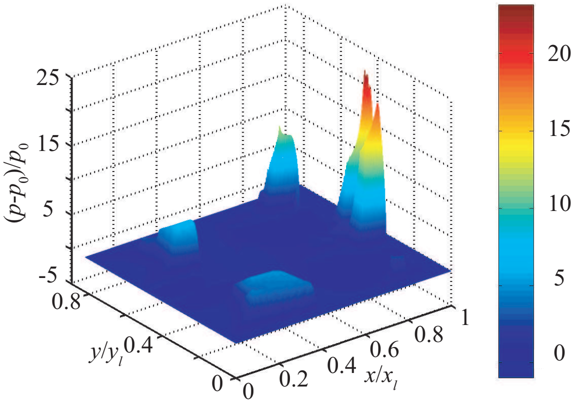

FIG. 2: Typical air pressure distribution on the ABS of the slider. The peak is located near the transducer. x and y are along the length and width directions of the slider respectively. x_l is the slider's length, p is air pressure in the head-disk interface (HDI) and p_0 is the ambient pressure outside the HDI.

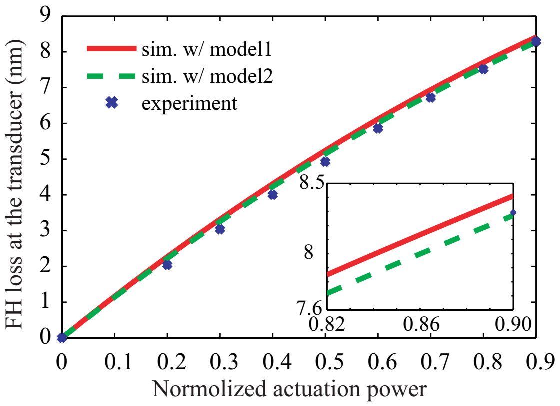

FIG. 3: The loss of the slider's flying height at the read-write transducer. The model 1 refers to the model based on the first order slip theory as represented by Eq. (1) and the model 2 refers to Chen et al.'s model with the modified mean free path in Eq. (2).

Figure 4 shows the relative difference in the minimum FH predicted by the current model and the new model. The difference increases as the slider's minimum FH decreases, but the difference, even for a minimum FH of 1.8nm, is only 7%. The main reason the difference is so small is due to the fact that the error presented in the current model appears only when the Knudsen number, defined as the ratio of the local mean free path (MFP) to the slider's

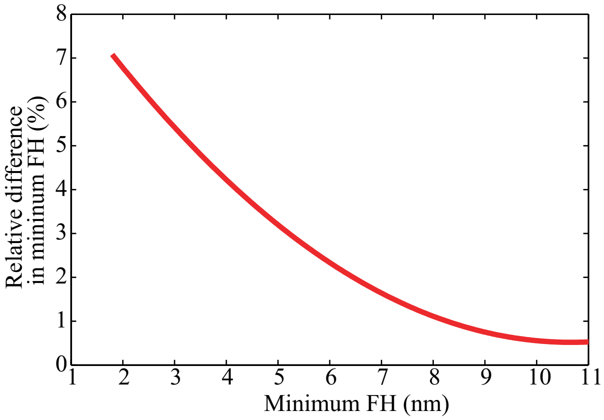

FIG. 4: Relative difference in minimum flying height predicted by the two models.

local FH, is very high [8]. Since the mean free path is inversely proportional to the local pressure and the pressure near the transducer is relatively quite high, the local MFP near the transducer is much smaller than the ambient MFP and therefore the Knudsen number underneath the read-write transducer is not very large. Thus, the current model does not cause much error in comparison with experiments, and the prediction based on the current model is close to that based on the more accurate new model.

In addition to heat conduction, heat dissipation induced by the moving air in the HDI also contributes to the total heat flux on the ABS. This effect is generally neglected [3] [4] but some researchers did include this effect in their calculation [13] [14] [15]. When this effect is included, the formula for heat flux on the ABS, Eq. (1), changes to [13]

$$q = -k \frac{T_s - T_d}{h + 2\frac{2-\sigma_T}{\sigma_T}\frac{2\gamma}{\gamma+1}\frac{1}{\mathrm{Pr}}\lambda} + \frac{1}{8}\rho U^2 \sqrt{\frac{8RT_0}{\pi}} \frac{\lambda}{h + 2\lambda} \tag{3}$$

where ρ is the density of the air, U is the disk's linear speed, T_0 is the ambient temperature outside the HDI, and R is the specific gas constant. Replacing Eq. (1) by Eq. (3) in our code does not produce any difference in the final results. This can be explained by comparing the order of the two terms in Eq. (3). As an estimation, we choose $\mathrm{Pr} = 2/3$, $\gamma = 1.4$, $\sigma_T = 1$, $T_0 = 300\mathrm{K}$, $k = 0.025\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})$, and $R = 287\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K})$. Since air density is proportional to pressure and mean free path is inversely proportional to pressure, $\lambda\rho = \lambda_0\rho_0$ where $\lambda_0 = 65\mathrm{nm}$, $\rho_0 = 1.204\mathrm{kg}/\mathrm{m}^3$, and quantities with a subscript 0 refer to their values at the ambient state. Then the ratio of the second term, representing the contribution of heat dissipation, to the first one, representing the contribution of heat conduction, becomes

$$2 \times 10^{-4} \frac{U^2}{T_s - T_d} \frac{h + 14\lambda/9}{h + 2\lambda} \sim 2 \times 10^{-4} \frac{U^2}{T_s - T_d} \tag{4}$$

As shown by numerical results, the heat transfer on the ABS is only significant near the transducer. For typical commercial HDDs, U is on the order of 10m/s and the temperature difference near the transducer $T_s - T_d$ is within 10K, which makes the ratio in Eq. (4) on the order of $10^{-3} - 10^{-2}$. Thus the contribution of heat dissipation is negligible and only contribution of heat conduction needs to be considered, agreeing with our numerical results.

In summary, a new phenomenological heat transfer model in which the mean free path is modified to include the effect of collisions between molecules and boundaries has been applied to the prediction of flying performance of thermal flying height control sliders. The air bearing cooling predicted by this model is stronger due to this modified mean free path, and this results in a reduced protrusion around the transducer. Simulation results based on the more accurate model compares well with experiments and are slightly better than those based on the traditional first order slip theory. The error induced by the current model based on the first order slip theory is less than 10% for state-of-art TFC sliders for which a pressure peak appears near the transducer and decreases the local mean free path and local Knudsen number. Unless the local Knudsen number near the transducer is quite large, the prediction based on the current model involves an error less than 10% and therefore it is sufficiently accurate. By numerical simulation and theoretical analysis, we also validate the current strategy of considering heat conduction induced by the moving air in the HDI as the unique contributor to the heat flux on the ABS.

Acknowledgments

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