Coupled Effects of Surface Roughness and Accommodation Coefficient for Ultra-Thin Gas Film Lubrication

Bao-Jun Shi (史宝军) [1,2], Kai Guo (郭凯) [2], Ya-Ru Sun (孙亚茹) [2], and Yu-Jie Feng (冯玉节) [2]

[1]School of Mechanical Engineering, Hebei University of Technology, Tianjin 300401, China
[2]School of Mechanical and Electrical Engineering, Shandong Jianzhu University, Jinan 250101, China

For modern magnetic disk drives, as the minimum flying height in the head-disk interface (HDI) is continuously reduced to about 1–2 nm, the surface roughness and the accommodation coefficient (AC) effects should be considered in addition to the gaseous rarefaction effect. However, only a few published papers had studied both the effects of these two parameters simultaneously. Based on the modified molecular gas film lubrication equation proposed for ultra-thin gas film lubrication, the coupled effects of the surface roughness, the AC, and the gaseous rarefaction in the HDIs are investigated for various groups of the surface roughness and the AC. Numerical results are presented and discussed to show the coupled effects on the pressure and the load carrying capacity of the film. Both the symmetrical and asymmetrical molecular interactions are studied and rational interpretations are given for the phenomena observed.

Index Terms—**Lubrication, magnetic heads, surface roughness, thin film.**

I. Introduction

THE clearance between the read/write head and the disk surface, which is normally referred to the flying height (FH), should be small and stable as the FH is one of the important parameters of the head-media spacing [1], [2]. For the purpose of reaching a higher areal density, the FH is continuously reduced to about 1–2 nm in today's magnetic disk drives [3], [4]. With such a narrow spacing in the head-disk interface (HDI), it is vital to consider the gaseous rarefaction and roughness effects of the air bearing film. By solving a modified Reynolds equation, the effects of gaseous rarefaction and surface roughness were investigated [5], [6]. Moreover, the surface accommodation coefficient (AC) of the slider and the disk also plays an important role to control the flying of the slider [7], [8]. The AC effect was investigated by solving a modified molecular gas film lubrication (MGL) equation [9], [10]. However, most of the published works considered gaseous rarefaction effects with either surface roughness or AC effects, rather than both of them simultaneously.

In this paper, based on the modified MGL equation in [11], both the surface roughness and the AC effects are considered simultaneously, in addition to the gaseous rarefaction effect. Numerical results are presented for various groups of surface roughness and AC in both symmetrical molecular interaction (SMI) and asymmetrical molecular (AMI) interaction.

II. Modified MGL Equation

For an infinitely wide plane slider, the modified MGL equation that takes the AC and surface roughness into account simultaneously can be described as follows [11], which is derived based on a simplified MGL equation [8] and a precise second-order model of Reynolds equation [12]:

$$\frac{d}{dX}\left(\begin{array}{l}\tilde{Q}_p(D,\alpha_1,\alpha_2)\varphi_x^p PH^3\dfrac{dP}{dX}\\ -\Lambda_x\tilde{Q}_c(D,\alpha_1,\alpha_2)P\left(H+\varphi^s H_{\text{so}}^{-1}\right)\end{array}\right)=0 \quad (1)$$

$$\tilde{Q}_p(D,\alpha_1,\alpha_2)=Q_p(D,\alpha_1,\alpha_2)/Q_{p,\text{con}}(D) \quad (2)$$

$$\tilde{Q}_c(D,\alpha_1,\alpha_2)=Q_c(D,\alpha_1,\alpha_2)/Q_{c,\text{con}}(D) \quad (3)$$

$$Q_p(D,\alpha_1,\alpha_2)=a+bD+cD^{-1} \quad (4)$$

$$Q_c(D,\alpha_1,\alpha_2)=a_1+a_2D+a_3D^{-1} \quad (5)$$

$$\varphi_x^p=1+\left(\frac{\sigma}{h}\right)^2\cdot\left(3+\frac{3a_2D-2a_3D^{-1}}{a_1+a_2D+a_3D^{-1}}\right) -\frac{1}{1+\gamma}\cdot\left(\frac{\sigma}{h}\right)^2\left(3+\frac{a_2D-a_3D^{-1}}{a_1+a_2D+a_3D^{-1}}\right)^2 \quad (6)$$

$$\varphi^s=\left(\frac{\sigma}{h}\right)\cdot\left(3+\frac{a_2D-a_3D^{-1}}{a_1+a_2D+a_3D^{-1}}\right) \cdot\left[\left(\frac{\sigma_1}{\sigma}\right)^2\frac{1}{1+\gamma_1}-\left(\frac{\sigma_2}{\sigma}\right)^2\frac{1}{1+\gamma_2}\right] \quad (7)$$

where P is the non-dimensional pressure of the film. H is the FH of the slider. X is the non-dimensional coordinate along the slider length direction. α_1 is the AC of the disk. α_2 is the AC of the slider. σ_1 is the surface roughness of the disk. σ_2 is the surface roughness of the slider. a, b, and c and a_1, a_2, and a_3 are coefficients and are shown in [8]. φ_x^p and φ^s are the pressure flow factor in the x-direction and the shear flow factor [5], respectively. γ (γ_1 and γ_2 are the Peklenik number of the disk and the slider, respectively) is the Peklenik number that was introduced to identify the surface roughness mode. D $(=(\sqrt{\pi}/2)K_n^{-1})$ is the inverse Knudsen number. K_n $(=\lambda/h_1)$ is the Knudsen number. λ is the molecular mean-free path. h_1 is the minimum FH. $Q_{p,\text{con}}(D)=D/6$ and $Q_{c,\text{con}}(D)=1$.

In the previous work [11], we investigated the combined effects of the surface roughness mode and the AC in the HDIs. In this paper, the roughness and the AC effects

Manuscript received March 5, 2018; revised April 20, 2018; accepted June 12, 2018. Corresponding author: B.-J. Shi (e-mail: shibj2003@126.com).
Digital Object Identifier 10.1109/TMAG.2018.2848967

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

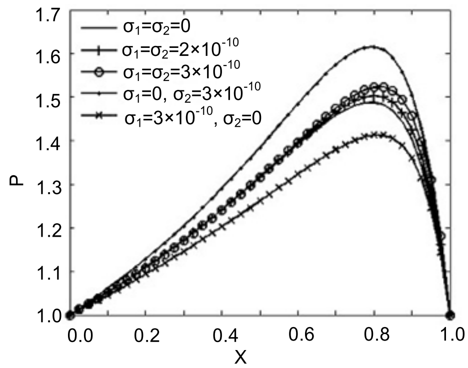

Fig. 1. Pressure distributions for different surface roughness with $\alpha_1 = \alpha_2 = 0.5$.

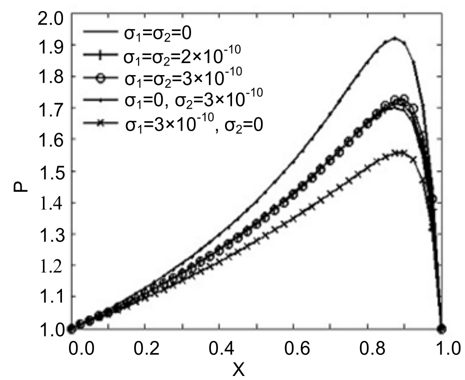

Fig. 2. Pressure distributions for different surface roughness with $\alpha_1 = \alpha_2 = 1.0$.

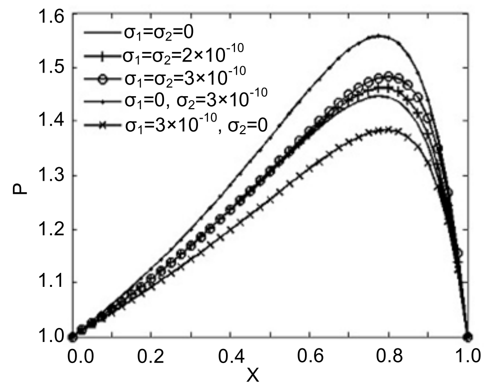

Fig. 3. Pressure distributions for different surface roughness with $\alpha_1 = 0.5$ and $\alpha_2 = 1.0$.

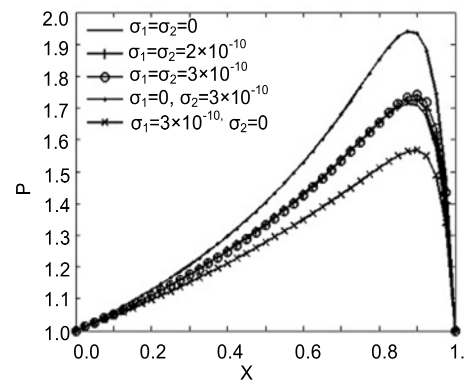

Fig. 4. Pressure distributions for different surface roughness with $\alpha_1 = 1.0$ and $\alpha_2 = 0.5$.

are simultaneously considered to further study their coupled effects on the pressure and the load carrying capacity (LCC) of the film.

III. Numerical Results and Discussion

The coupled effects of the surface roughness, the AC, and the gaseous rarefaction effect on the pressure and the LCC are presented and discussed in this section. In this paper, the disk velocity is 5400 rpm. The minimum FH of the slider is 1 nm, and the Peklenik number of the slider and the disk is fixed at 0.5, which indicates that the roughness modes of the slider and the disk are fixed at the given roughness mode.

A. Effects on Pressure

Figs. 1 and 2 show the pressures for various surface roughness groups in two cases of SMI ($\alpha_1 = \alpha_2$). There are five curves in each figure. The solid one without any mark represents the "smooth" case, in which both the slider and the disk have no roughness. The two solid curves with marks of plus (+) and circle (◯) represent two roughness cases, in which both the slider and the disk have the same roughness of 0.2 and 0.3 nm, respectively. The two solid curves with marks of product sign (×) and point (·) represent another two roughness cases, in which either the disk or the slider only has a roughness of 0.3 nm, respectively.

From Figs. 1 and 2, we have the following observations.

1) If both the slider and the disk have roughness, the pressure will increase with the increase of the AC, while the maximal pressure moves toward the trailing edge of the slider.
2) If the slider only has roughness, the pressure is much higher than that of the "smooth" case in which both the slider and the disk have no roughness. However, if the disk only has roughness, the pressure is much lower than that of the "smooth" case.
3) In general, in the SMI case, the pressure of the film increases with the increase of ACs with various surface roughness groups. For a given surface roughness, the pressure increases obviously if the slider only has roughness, whereas it decreases obviously if the disk only has roughness. This is because if the slider only has roughness, the shear flow factor plays a negative effect on the gas flowing, and the gas flowing in the x-direction will be suppressed, which results in the pressure increase of the film in this case. By contrary, if the disk only has roughness, the shear flow factor plays a positive effect on the gas flowing, and the gas flowing in the x-direction will be accelerated, which results in the pressure decrease in this case.

Figs. 3 and 4 show the pressure for various surface roughness combinations in the case of AMI ($\alpha_1 \neq \alpha_2$).

Fig. 5 demonstrates the pressure for various ACs of the disk if the AC of the slider is fixed at 0.5. Fig. 6 shows the pressure for various ACs of the slider if the AC of the disk is fixed at 0.5. The roughness of the disk and the slider are fixed at 0.3 nm.

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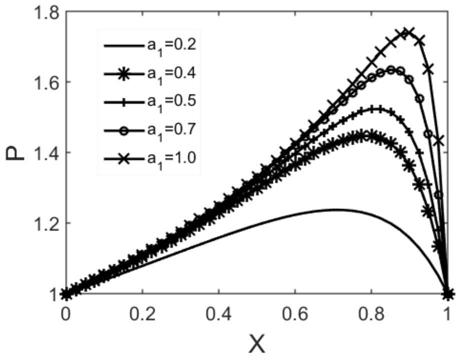

Fig. 5. Pressure distributions for various ACs of the disk when the AC of the slider is 0.5.

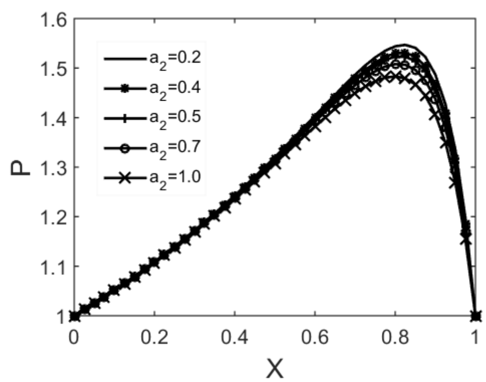

Fig. 6. Pressure distributions for various ACs of the slider when the AC of the disk is 0.5.

Based on the comparisons between Figs. 2 and 3 or Fig. 4, as well as Figs. 5 and 6, we have the following observations.

1) The pressure decreases significantly if the AC of the disk (α_1) decreases from 1.0 to 0.5 as shown in Figs. 2 and 3.
2) The pressure has almost no change to an extent if the AC of the slider (α_2) decreases from 1.0 to 0.5 as shown in Figs. 2 and 4.
3) With the increase of AC of the disk, the pressure increases obviously and the maximal pressure moves toward the trailing edge of the slider if the AC of slider remains at a fixed value as shown in Fig. 5.
4) With the increase of AC of the slider, the pressure decreases slightly and the maximal pressure moves away from the trailing edge of the slider if the AC of disk remains at a fixed value as shown in Fig. 6.
5) The above-mentioned observations of the third and fourth points indicate that for the same and given roughness of the disk and the slider, the AC of the disk has a positive and strong effect on the pressure for a given slider AC, whereas the AC of the slider has a negative and weak effect on the pressure for a given disk AC.
6) In general, the ACs changes of the slider and the disk have opposite influences on the pressure with different degrees. This phenomenon can be explained using the relationship between the Couette flow rate and the ACs [8]. It has indicated that the Couette flow rate decreases with the decrease of the disk's AC, which will weaken the pressure of the film.

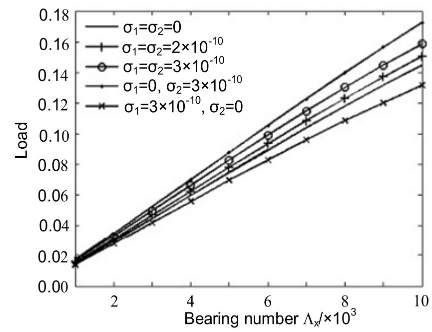

Fig. 7. LCCs for different surface roughness with $\alpha_1 = \alpha_2 = 0.5$.

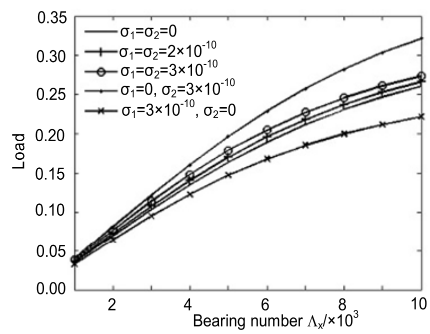

Fig. 8. LCCs for different surface roughness with $\alpha_1 = \alpha_2 = 1.0$.

B. Effects on LCC

Figs. 7 and 8 show the profiles of the LCCs of the film versus the bearing numbers for different surface roughness groups in two SMI cases ($\alpha_1 = \alpha_2$).

From Figs. 7 and 8, we have the following observations.

1) If both the slider and the disk have roughness, the LCC will increase with the increase of the AC. The LCC also increases with the increase of the surface roughness. However, the increasing rate of the LCC is non-linear for the higher AC, whereas it is almost linear for the lower AC.
2) If the slider only has roughness, the LCC is much higher than that of the "smooth" condition. However, if the disk only has roughness, the LCC is much lower than that of the "smooth" condition.
3) In general, in the SMI case, the LCCs of the film increase with the increase of ACs and/or the bearing number with various surface roughness groups. For a given surface roughness and compared with the "smooth" condition, the LCC increases if the slider only has roughness, whereas it decreases if the disk only has roughness. These observations can also be explained based on the effect of the shear flow factor on the gas flowing as those stated for the pressure in the SMI case.

Figs. 9 and 10 show the LCCs of the film versus the bearing numbers for different surface roughness groups in two AMI cases ($\alpha_1 \neq \alpha_2$).

Fig. 11 shows the profiles of the LCCs of the film as a function of bearing numbers for various ACs of the disk if the AC of the slider is fixed at 0.5. Fig. 12 shows the profiles of the LCCs of the film versus the bearing numbers for various ACs of the slider if the AC of the disk is fixed at 0.5.

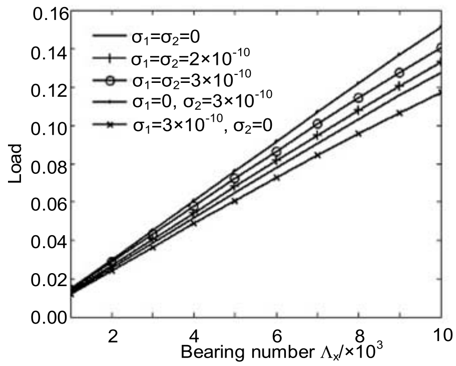

Fig. 9. LCCs for different surface roughness with $\alpha_1 = 0.5$ and $\alpha_2 = 1.0$.

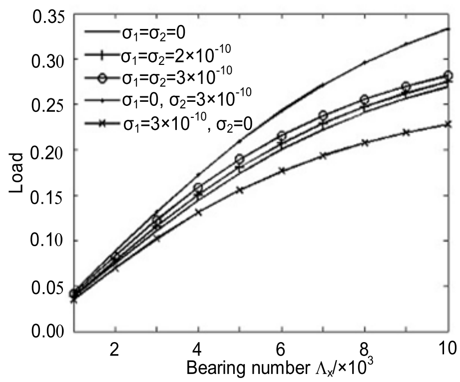

Fig. 10. LCCs for different surface roughness with $\alpha_1 = 1.0$ and $\alpha_2 = 0.5$.

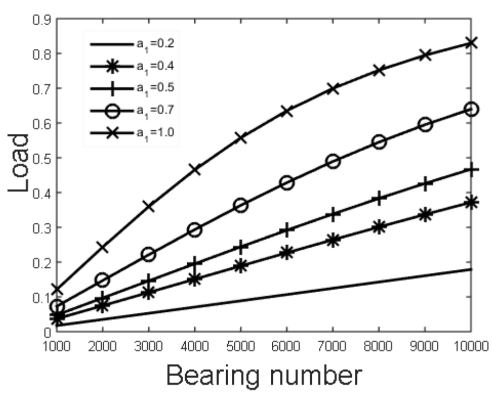

Fig. 11. LCCs for various ACs of the disk when the AC of the slider is 0.5.

Based on the comparisons between Figs. 8 and 9 or Fig. 10, as well as Figs. 11 and 12, we have the following observations.

1) The LCCs decrease significantly if the AC of the disk (α_1) decreases from 1.0 to 0.5 as shown in Figs. 8 and 9.
2) The LCCs increase slightly if the AC of the slider (α_2) decreases from 1.0 to 0.5 as shown in Figs. 8 and 10.
3) As shown in Fig. 11, with the increase of AC of the disk, the profiles of the LCCs increase obviously if the AC of slider remains at a fixed value. Meanwhile, the increasing rate of the LCC versus the bearing number is non-linear for the higher AC of the disk, whereas it is almost linear for the lower AC of the disk.

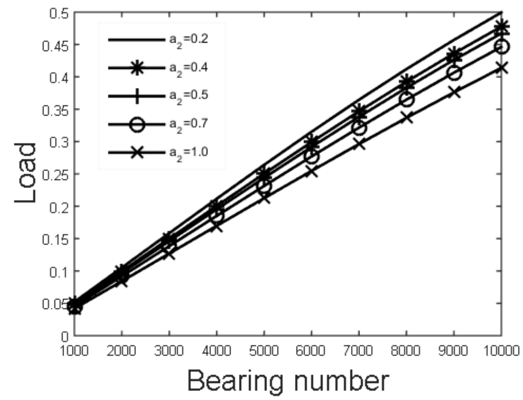

Fig. 12. LCCs for various ACs of the slider when the AC of the disk is 0.5.

4) As shown in Fig. 12, with the increase of ACs of the slider, the profiles of the LCCs decrease slightly if the AC of disk remains at a fixed value. Meanwhile, the increasing rate of the LCC versus the bearing number is almost linear for all the AC of the disk.
5) The above-mentioned observations of the third and fourth points indicate that for the same and given roughness of the disk and the slider, the AC of the disk has a positive and strong effect on the LCC for a fixed AC of the slider, whereas the AC of the slider has a negative and weak effect on the LCC for a fixed AC of the disk.
6) In general, the ACs changes of the slider and the disk have opposite effects on the LCCs with different degrees. The explanations of these observations are the same as those stated for the pressure in the AMI case.

IV. Conclusion

1) Based on the modified MGL equation proposed for ultra-thin gas film lubrication, the coupled effects of the surface roughness, the AC, and the gaseous rarefaction effect on the pressure and the LCC of the film in HDIs are investigated in this paper.
2) In SMI case, the pressure and the LCC of the film increase with the increase of ACs and/or the bearing number with various surface roughness groups. For a given surface roughness values and compared with the "smooth" condition, the pressure and the LCC of the film increase if the slider only has roughness, whereas it decreases if the disk only has roughness. The observed phenomena are explained based on the effect of the shear flow factor on the gas flowing.
3) In AMI case, the ACs changes of the slider and the disk lead to opposite effects on the pressure and the LCC. These observed phenomena are explained based on the effect of the Couette flow rate on the gas flowing.

Acknowledgment

This work was supported in part by the National Nature Science Foundation of China under Grant 51275279 and in part by the Tribology Science Fund of State Key Laboratory of Tribology under Grant SKLTKF16A01, China.

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