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MODELING AND ANALYSIS ON THIN-FILM FLOW OVER A ROUGH ROTATING MAGNETIC DISK

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The depletion of thin liquid films due to the combined effect of centrifugation, surface roughness, and air-shear has recently been studied. While surface roughness of a rotating solid disk can be represented by deterministic curves, it has been argued that spatial random processes provide a more realistic description. Chiefly because of surface roughness, there is an asymptotic limit of retention of a thin film flowing on the rotating disk. The aim of this article is to model the depletion of thin-film flow and analyze the interplay of centrifugation, surface tension, viscosity, air-shear, disjoining pressure, and surface roughness that affect the depletion of the film. Also, the robustness of stochastic description of surface roughness is examined.

I. INTRODUCTION

Recording in rigid magnetic storage disks is accomplished by the relative motion of the rigid disk against a stationary read/write magnetic slider. During steady operating conditions, a load-carrying air film is formed. When the unit is first started or turned off, however, the slider lacks the air bearing and slides in contact with the disk. In order to protect the disk as well as the slider from excessive wear, a thin layer of film is applied to the surface of the disk during the manufacturing process. This lubricant exists in the form of a thin film of viscous liquid, which has 10-30 nm thickness for a particulate disk and 0.5-4.0 nm for a thin-film disk. The thin-film layer tends to drift outward because of the rotation of the disk drive, which may spin at thousands of revolutions per minute. Since it is important that a sufficient amount of thin-film should always remain on the disk, the study of the detailed mechanism that holds the thin-film onto the surface becomes an important issue.

The flow of a viscous layer over a smooth rotating disk has been considered in the literature[1-5], with particular relevance to spin-coating. In a well-known investigation, Emslie, Bonner, and Peck[1] developed a model of Newtonian flow on a smooth surface to obtain the distribution of the liquid as a function of time. The influence of air-shear, surface tension, disjoining pressure, and surface roughness was neglected in their investigation. Middleman [2], Rehg and Higgins[5] studied the effect of air-shear on spin-coating. They observed significant increase in depletion due to the induced air-flow on the free liquid surface. McConnell[3] has recently conducted experiments to demonstrate the validity of the classical model of Emslie *et al.* when air-shear can be neglected. For conditions where air circulation takes place, McConnell has also obtained data that would qualitatively support the observations of Middleman. Thus, the models developed by Emslie *et al.* and Middleman may be employed in applications with reasonable confidence. For the case of very thin liquid layers, however, it is known that the theoretical predictions of both models have appreciably exaggerated the thinning of the liquid film at large values of time. Based upon extensive experimental data, it is thought that the discrepancy arises mainly from the omission of surface roughness in the above models. Eventually the asymptotic retention of a liquid layer may represent a compromise between surface roughness, centrifugation, surface tension, air-shear, and disjoining pressure.

The primary goal of this study is to model the depletion of thin-film flow and analyze the interplay of centrifugation, surface tension, air-shear, disjoining pressure, and surface roughness that affect the depletion of the film. Also, the robustness of stochastic description of surface roughness is examined. For random topography, disk surfaces with Gaussian distribution of the heights are constructed. Using different realizations of the random disk surface, Monte Carlo simulations are performed to determine the mean retention of a thin film. Comparison of retention characteristics for different surfaces leads to important observations on the influence of topographic structure on thin-film flow. This study may contribute to devising algorithms for texturing thin-film disks. From a design standpoint, there may exist a roughness pattern that minimizes stiction and maximizes the asymptotic limit of thin-film retention, and this study could be a step in uncovering the pattern.

II. MODELING OF THIN-FILM FLOW

In developing a model of viscous flow over a rough rotating disk, it is assumed[1-5] that (i) the plane of the rotating disk is horizontal, (ii) the liquid layer is radially

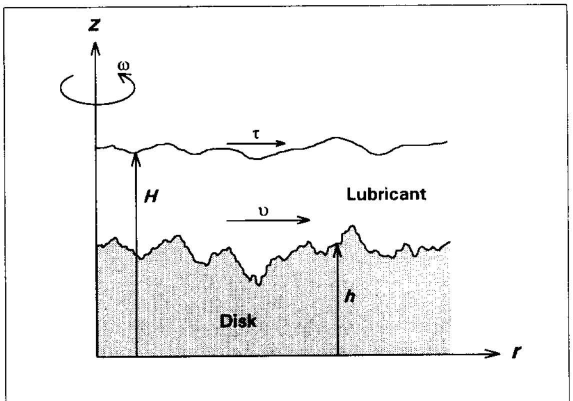

Fig. 1. Thin-film flow over a rough rotating disk.

symmetric, and so thin that gravitation has negligible effect in distributing the layer, (iii) the flow is Newtonian and nonvolatile, with a radial velocity so small that Coriolis forces may be ignored, and (iv) the radial velocity of the induced air-flow is substantially greater than that of the liquid layer. A system of cylindrical coordinates (r, θ, z) that rotates with the disk at an angular velocity ω about the z-axis is used. The situation is clarified in Fig. 1, in which z=0 is a reference elevation which may conveniently be taken as the center of the thickness of the disk, $v(r,z,t)$ is the radial velocity of the liquid, $h(r)$ is the height of the rough solid surface, and $H(r,t)$ is the height of the free surface of the liquid. When the above assumptions are incorporated in the Navier-Stokes equation, the equation describing the flow of a thin liquid film takes the form

$$-\eta\frac{\partial^2 v}{\partial z^2}=\rho\omega^2 r-\frac{\partial P}{\partial r}\ , \qquad (1)$$

where η is the dynamic viscosity, ρ is the density of the liquid, and P is a nonclassical term given by

$$P=\frac{\gamma}{R}-\Pi\ . \qquad (2)$$

In the above, γ is the coefficient of surface tension, Π is the disjoining pressure function, and R is the curvature of the free liquid surface in the radial direction written as

$$\frac{1}{R}=-\left\{\frac{\partial^2 H}{\partial r^2}+\frac{1}{r}\frac{\partial H}{\partial r}\left[1+\left(\frac{\partial H}{\partial r}\right)^2\right]\right\}\times\left[1+\left(\frac{\partial H}{\partial r}\right)^2\right]^{-3/2}\ . \qquad (3)$$

Generally, the disjoining pressure function can be expressed as an infinite series involving inverse powers of the liquid film thickness. It has recently been suggested through experiments that for a relatively smooth liquid-solid interface, the total disjoining pressure can be expressed in the form[8]

$$\Pi=-\frac{A_2}{(H-h)^2}+\frac{A_3}{(H-h)^3}\ , \qquad (4)$$

where A_2 is of the order 10^{-12}N and A_3 is of the order 10^{-19} N · cm. Assuming that there is no flow on the disk surface, the boundary condition at liquid-solid interface is

$$v(r,h,t)=0\ . \qquad (5)$$

The boundary condition at the liquid-air interface can be written as

$$\eta\frac{\partial v}{\partial z}(r,H,t)=\tau\ , \qquad (6)$$

where τ is the shear stress directed radially on the free surface of the thin-film. If assumption (iv) is satisfied, the shear stress τ may be given by the approximation[2]

$$\tau=\left(\frac{1}{2}\,\omega^{\frac{3}{2}}\,\nu_{air}^{-\frac{1}{2}}\,\eta_{air}\right)r, \qquad (7)$$

where ν_{air} is the kinematic viscosity of air, and $\eta_{air}=\rho_{air}\nu_{air}$ is the corresponding dynamic viscosity. Defining the radial flow per unit length by

$$q=\int_h^H v\,dz, \qquad (8)$$

the continuity equation can be written as

$$r\frac{\partial H}{\partial t}=-\frac{\partial}{\partial r}(rq). \qquad (9)$$

Equations (1) and (9), together with the appropriate initial and boundary conditions, provide a description of the flow of a thin viscous film over a rough rotating disk. The depletion of the liquid layer is governed by six factors: centrifugation, surface tension, viscosity, air-shear, disjoining pressure, and surface roughness. Any rough disk surface can be considered by prescribing the function $h(r)$, and the solution of the above equations will yield the free thin-film surface $H(r,t)$.

To examine the robustness of stochastic modeling of surface roughness for a magnetic storage disk, the heights of rough surface is prescribed in turn by different probability distributions all of which possess an exponential type correlation structure. The distribution types employed in this study are log-normal, beta, uniform, and the Gaussian. Now, it has been observed by experiments that there are isolated pores scattered on the surface of a particulate disk, the dimensions of these pores being one order of magnitude larger than the minute fluctuations of the heights. It means that two length scales would be required to characterize the surface asperities of a particulate disk. The small-scale roughness is represented by the various probability distributions describing fluctuations of the heights of the disk surface. To model the large-scale surface asperities, a sequence of random locations on the disk surface is generated such that the distance between the locations follow an exponential density function. These random locations serve as centers around which the large-scale pores are constructed. The exponential distribution is used for the separation between random locations because of its Markov, or memoryless, property. The depth of each pore is first generated using the same distribution type as that employed in describing the small-scale roughness, each with mean μ_p and standard deviation σ_p. The shape of each pore is then obtained by a process of controlled Brownian motion [7]. When the small-scale and large-scale surface asperities are superimposed upon each other, the resulting surface possesses two length scales in surface asperities, and such a model appears to provide an adequate characterization of the surface topography in two dimensions with radial symmetry. For each distribution type, a sufficiently large number of spatial blocks has been used to secure deterministic convergence and accuracy. A total of M=250 Monte Carlo passes with stratified sampling is employed, which in every case is found to be greater than the number of cycles required for convergence of the output data within 0.1 % error. The volume of thin-film retained on the disk can then be obtained by integration. The volume of thin-film that remains on the rotating disk at t is given by

$$Q(t) = 2\pi \int_0^{r_{max}} [\ H(r,t) - h(r)]\ dr, \qquad (10)$$

where r_{max} is the radius corresponding to the edge of the disk.

A Crank-Nicolson finite difference scheme is used to solve the equations of viscous flow[6]. This numerical scheme has been found to be quite stable, with global error of the order $O[\ (\Delta t)^2, (\Delta r)^2]$

Ⅲ. SIMULATION RESULTS

The results of several simulations will be reported in this section primarily to highlight the effect of centrifugation, surface tension, viscosity, air-shear, disjoining pressure, and surface roughness aw well as the robustness of stochastic description of surface asperities on the depletion of a thin film layer. After non-dimensionalization, several important factors are defined as follows

$$N_{ar} = \frac{H_0}{R_0},\quad N_B = \frac{\rho\omega^2 R_0^3}{\gamma},\quad N_{ratio} = \frac{N_{ar}}{N_B}, \qquad (11)$$

$$N_{dm} = \frac{3A_3}{\rho\omega^2 H_0^3 R_0^2},\quad N_{de} = \frac{2A_2}{\rho\omega^2 H_0^2 R_0^2}, \qquad (12)$$

$$N_{af} = \frac{3\left(\frac{1}{2}\ \omega^{\frac{3}{2}}\ \nu_{air}^{-\frac{1}{2}}\ \eta_{air}\right)}{2\rho\omega^2 H_0}, \qquad (13)$$

where R_o can be chosen as a characteristic length of roughness in the r-direction, and H_o as a typical initial height of the free surface of the film. A plausible choice for the time scale is that associated with the initial rate of centrifugal spinoff given by $\frac{3\eta}{\rho H_0^2 \omega^2}$. The dimensionless constants N_{ar} and N_B are, respectively, the characteristic aspect ratio of roughness and Bond number of the liquid film. The Bond number represents the ratio of the effect of centrifugation to the effect of surface tension. The dimensionless constants N_{dm} and N_{de} are respectively the ratios of molecular and electrostatic contributions of disjoining pressure to centrifugation. In addition, the dimensionless constant N_{af} represents the ratio of air-shear effect to centrifugation effect. The nondimensional ratio N_{ratio} is, in a certain way, a ratio of the surface tension effect to the centrifugation effect. A set of realistic dimensional values is to have ω, γ, ρ, ρ_{air}, η, η_{air}, H_o, and R_o equal to 100π rad/s, 20.0 dyn/cm, 1.9 g/cc, 1.18×10^{-3}g/cc, 1.0 g/(cm · s), 1.81×10^{-4} g/(cm · s), 50.0 nm, and 2.0 μm, respectively.

A. Centrifugation Depletion of thin-film is caused by the centrifugation effect due to the rotation of the disk. Coupled effect with others will discussed in other sections.

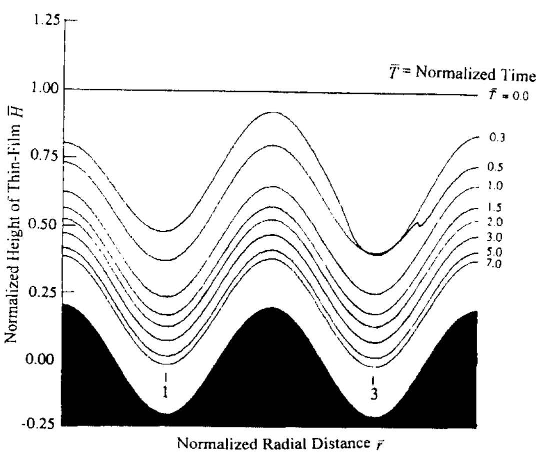

Fig.2. Successive free surface contours for thin-film over a sinusoidal disk surface.

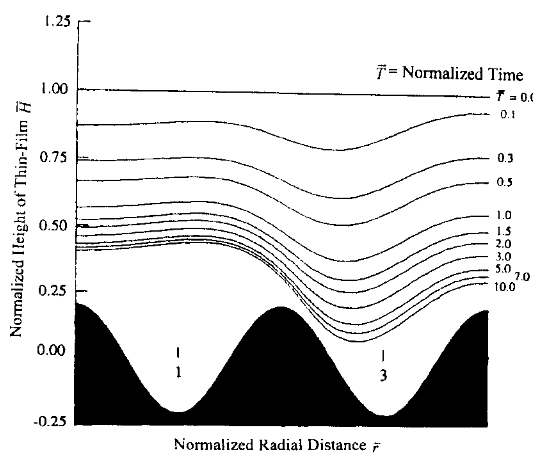

Fig.3. Successive free surface contours for thin-film over a sinusoidal bottom surface with $N_{ratio} = 1.0$.

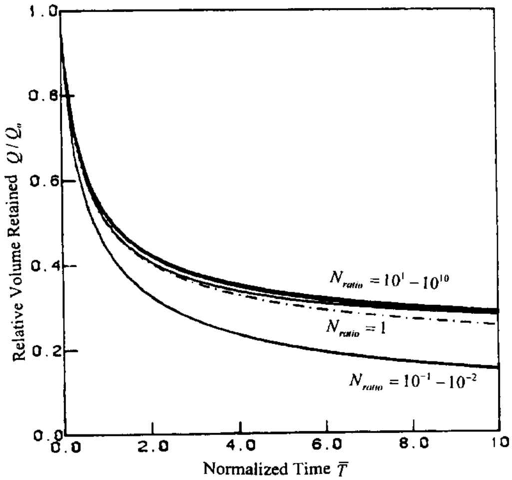

Fig.4. The effect of N_{ratio} on thin-film retention.

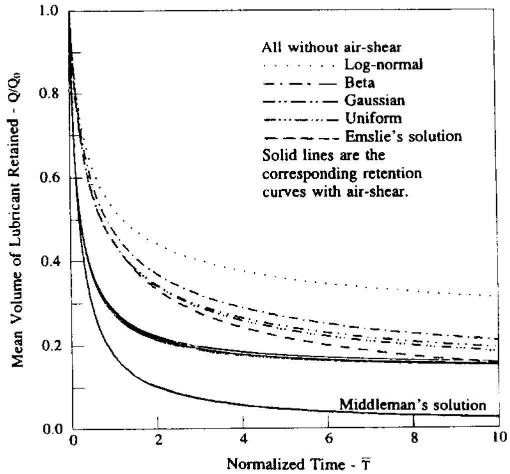

Fig.6. Thin-film retention for different probability distributions.

B. Surface Tension Physically, the effect of surface tension is to reduce any non-uniformity of the free liquid surface as shown in Fig. 3. Fig. 2 is the case of no surface tension. Surface roughness markedly enhances the retention of thin-film if surface tension is incorporated. Retention characteristics of the thin-film are rather insensitive to change in the value of N_{ratio} when it lies between 10 and 10^{10} as in the Fig. 4.

C. Air-shear The retention curve of the thin-film under various conditions is given in Fig. 5. As shown in the figure, air-shear greatly increases the depletion of thin-film. However, surface roughness eventually dominates over air-shear.

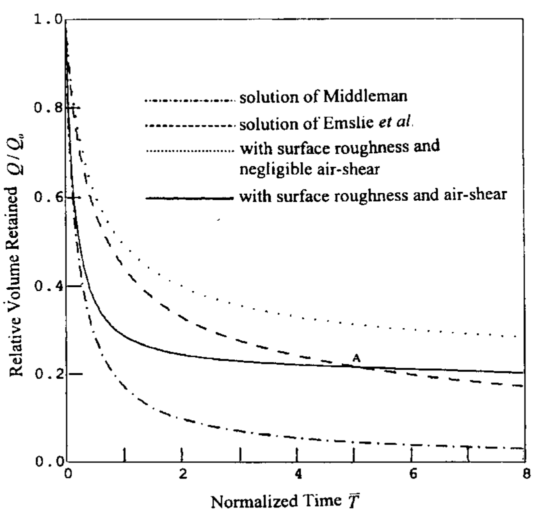

Fig.5. Thin-film retention under various conditions.

D. Disjoining Pressure As long as the initial distribution of the height of thin-film is uniform, neither surface tension nor disjoining pressure is found to appreciably enhance the retention of thin-film. Disjoining pressure effect is secondary to surface tension effect across a wide range of magnitudes, and they agree with the discussion given by McConnell[3], who has found no experimental evidence to suggest that the disjoining pressure effect is first-order.

E. Robustness of Stochastic Modeling Computation of depletion is performed repetitively for many different realizations, and the results are analyzed statistically. Measured from a nominally flat disk surface, it has been assumed that $\mu_h = 0.0$ and $\sigma_h = 0.02$ for the small-scale roughness. Furthermore, the small-scale fluctuations are homogeneously correlated with a correlation function $\rho(x)$ given by

$$\rho(x) = e^{-(1/\lambda)|x|}, \qquad (14)$$

where x denotes the separation between two points to be correlated, and λ is a specified parameter which can be thought of as the average correlation length[6]. Set $\lambda / \bar{r}_{max} = 0.5$, where $\bar{r}_{max}$ is the radius of the disk. Superimposed upon the small-scale fluctuations are the large-scale fluctuations. It is assumed that the large-scale roughness consists of pores with a mean depth μ_p and standard deviation σ_p, both of which can be varied. The centers of the large-scale pores are separated by an exponential density function with mean fixed at 2.5. Except for μ_p and σ_p, all parameters that describe the random surface roughness are therefore fixed. In the absence of air shear, the thin-film retention is represented by the dashed line in Fig. 6 which is identical to the classical retention curve derivable from the solution of Emslie *et al.*[1].

When air-shear effect is included, the retention curve is plotted in Fig. 6 as a solid line which is derivable from the analysis of Middleman[2]. The figure demonstrates that air shear greatly increases the depletion of thin-film.

The dotted lines in Fig. 6 represent the retention curves associated with the different probability distributions of the surface roughness. For all distribution types, the dimensionless mean μ_p and standard deviation σ_p are fixed at 1.6 and 1.0, respectively. It can be seen that the curves begin to diverge at early stages and eventually lead to a wide disparity in the asymptotic retention level. Notice also that the log-normal distribution leads to a substantially higher thin-film retention level compared to the other three cases. This means that the stochastic model of surface roughness is not robust: thin-film retention is quite sensitive to the stochastic description of the surface asperities. For this reason, measurement of the mean and variance of surface roughness is not sufficient to determine the asymptotic limit of retention of a liquid layer. Irrespective of the distribution types used, however, the retention curves all lie above the curve derivable from the solution of Emslie *et al.*

When air-shear effect is incorporated, Fig. 6 shows that all retention curves fall inside of a fairly narrow band, implying that sensitivity to stochastic description is much attenuated. One possible explanation is that air-shear effect is more pronounced than surface roughness effect in the early stages of depletion history; it leads to more rapid thin-film depletion that does not greatly depend on the type of surface topography.

The dependence of lubricant retention on the degree of randomness of surface topography as measured by σ_p is examined in Fig. 7. It has been found that the mean volume of thin-film retained increases with σ_p for all distribution types employed in this study. In Fig. 7, beta and log-normal distributions with mean μ_p= 4.2 and standard deviation σ_p= 0.4, 2.0, and 8.0 are used. To explain the increase in asymptotic retention level, observe that a larger value of σ_p implies greater variations in the size of the pores. It is believed that the larger pores more than compensate for the smaller pores in lubricant retention; the existence of these larger pores elevates the mean volume of lubricant retained.

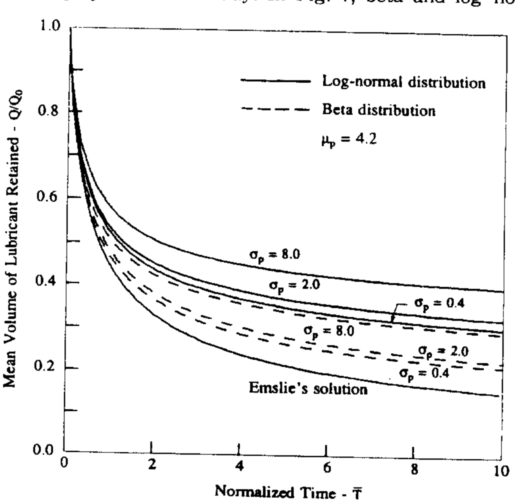

Fig.7. Comparison of retention for different values of σ_p.

IV. CONCLUSIONS

A course of study to investigate the combined effect ofcentrifugation, surface tension, viscosity, air-shear, disjoining pressure, and surface roughness aw well as the robustness of stochastic description of surface asperities on the depletion of thin-flim flow has been presented. Although a limited set of data from simulations is presented, extensive numerical calculations have been performed, and all numerical simulations have yielded identical qualitative results on liquid retention. The results stated in this study, we believe, are both reliable and important. However, these results have been obtained from a radially symmetric model of flow, and as such they are only as credible as the assumptions underlying the model. Among other things, it is hoped that this study would serve to point to directions along which further research efforts should be made. Three-dimensional random roughness can be generated if the flow is extended to depend on the angular orientation. The study of the influence of other factors, such as the vertical flow of the thin-film and disturbances induced by the slider may be worthwhile in a subsequent course of investigation.

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