Lubricant Retention on a Spinning Disk

Lisa Strong
Stanley Middleman
Department of AMES/Chemical Engineering and The Center for Magnetic Recording Research
University of California, San Diego
La Jolla, CA 92093

Rigid magnetic recording disks are created with a thin (submicron) layer of lubricating fluid, the purpose of which is to prevent damage (loss of data) from physical contact between the read-write head and the disk. Disks rotate at very high rotational speeds (typically, 3,600 rpm, though not continuously) and are expected to be reliable on a time scale of the order of years. Hence, long-time retention of lubricant is a significant issue in the design of a disk, its lubricant, and the container or housing surrounding the disk. Figure 1 shows the geometry of interest to us.

The two primary mechanisms of lubricant loss are evaporation and spinoff. While typical lubricants are involatile by ordinary standards, having vapor pressures at 300 K in the range of 10^{-4} to 10^{-10} N/m^2, the required time scale of retention (1 year = 3×10^7 s) is sufficiently long that evaporation is in fact a serious issue for the more volatile lubricants. This is especially so since disk rotation induces an evaporation-enhancing convective flow at the lubricant/air interface. This latter problem has been modeled by Salehizadeh *et al.* (1987), who provide estimates of evaporation times for several commercial lubricants.

In our work we focus on the fluid dynamics of spinoff by assuming that the lubricant is involatile. While this problem is of practical interest as suggested in the remarks of the preceding paragraphs, the spinoff problem also has some elements of fundamental fluid dynamics that are of intrinsic interest. These elements arise from the fact that the lubricating layer is extremely thin, often of the order of tens of nanometers. For these *polymeric* lubricants, therefore, the liquid film may be only some tens of molecular dimensions thick, *at most.* Of course this fact raises an immediate issue: can classical fluid dynamics based upon the continuum approximation serve as an appropriate basis for the modeling of lubricant flow in such a thin layer? A second interesting issue also arises from the fact that the liquid film is so thin. While the rigid disk substrate is extremely smooth by most standards, the surface does have a roughness amplitude of the order of several nanometers. Hence, we are interested in the flow of thin liquid films over surfaces that are in fact very rough by comparison to the mean liquid film thickness.

In the work reported here, we focus almost entirely on the first issue. We review a mathematical model of lubricant spinoff based upon classical fluid dynamics and present data in good agreement with this model for liquid films as thin as ten nanometers.

Theory

The simplest theory that can be applied to the spinoff problem is the classical spin *coating* theory of Emslie *et al.* (1958). This leads to a model of the transient film thickness on a rotating disk which we may write in the form

$$\tau = \frac{1}{2}\left(\frac{1}{H^2} - 1\right) \tag{1}$$

where $H = h(t)/h_0$ is a dimensionless film thickness, and τ is a dimensionless time variable defined by

$$\tau = (2\rho\omega^2 h_0^2/3\mu)t \tag{2}$$

Equation 1 is based upon the following assumptions:

- The liquid is Newtonian and isothermal.
- The solid planar substrate is perfectly smooth.
- A no-slip boundary condition holds at the liquid/solid boundary.
- There is no shear stress at the liquid/gas interface.
- The film thickness is initially uniform ($h = h_0$).
- The liquid is involatile.

While any of these assumptions could be inappropriate in some specific case of practical interest, we have chosen to retain all of them except "no shear stress at the liquid/gas interface." Because of the high rotation speed, the disk acts as a centrifugal pump. A significant air flow is induced toward the disk and then radially outward. This outward air flow has the capacity to exert a radially directed viscous shear stress at the liquid/gas interface, and thereby to aid the radial outflow of the liquid film. We refer to this phenomenon as "wind shear." Figure 2 shows this situation.

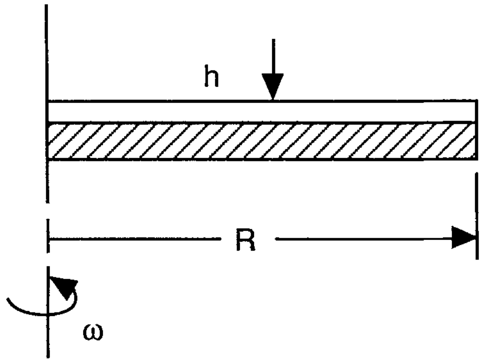

Figure 1. Geometry of rotating disk system.

A wind-shear theory of spinoff was developed by Middleman (1987). It begins with the quasi-steady lubrication approximation to the Navier-Stokes equations. In order to account for windshear, it is necessary to solve for the air flow induced by the rotation of the disk. No such solution is available for the case of a liquid-coated disk of finite radius enclosed within a housing of some kind. However, there is a classical solution due to Cochran (1934) which considers an infinite disk in a semiinfinite fluid.

In applying this result to develop a theory of wind-shear-aided spinoff, Middleman (1987) assumed that the radial velocity of the viscous liquid lubricant was so small, by comparison, to a velocity scale for the induced air flow that the lubricant was effectively stationary. This permitted the use of a no-slip boundary condition at the air-lubricant boundary. Of course the use of Cochran's expression for shear stress implies that the disk behaves as if it has an infinite radius, and that the boundaries of the disk drive do not alter the induced air flow, at least near the disk surface.

Schlichting (1960) discusses Cochran's theory and points out that the theory yields accurate predictions of the *tangential* (he does not comment on the radial) shear stress so long as a Reynolds number criterion is met, in the form

$$N_{Re} = \frac{R^2\omega}{\nu_{air}} < 3 \times 10^5 \tag{3}$$

This criterion can be met for an 8-cm radius disk rotating at 6,000 rpm in air at atmospheric pressure.

Details of the wind-shear analysis are presented in Middleman (1987). The result of interest to us here is the $H(\tau)$ relationship, which has the form

$$\tau = \beta\left(\frac{1}{H} - 1\right) - \beta^2 \ln\left(\frac{1 + \beta H}{H(1 + \beta)}\right) \tag{4}$$

A new parameter, β, appears, defined as

$$\beta = \frac{4}{3}\frac{h_0\omega^{1/2}}{\nu_{air}^{1/2}}\frac{\rho}{\rho_{air}} \tag{5}$$

We refer to β as a "wind-shear parameter."

Under conditions of interest to us here, β is a large number, typically of order 10^4. Figure 3 casts Eq. 4 in a format that simplifies calculations in the region of practical interest. In this region, τ/β^2 is a function of βH.

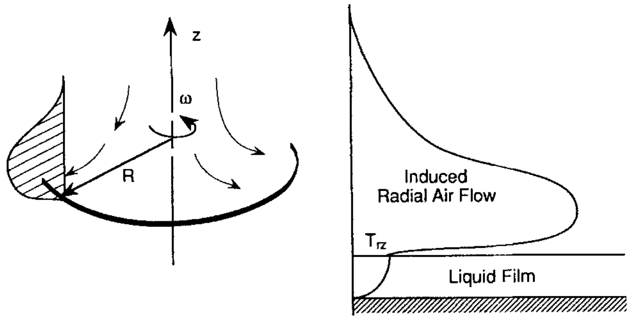

Figure 2. Air flow induced by disk rotation.
The radial shear stress at the liquid/air boundary is called "windshear."

Experimental Procedure and Results

An experimental program has been carried out with the goal of testing the limits of the wind-shear model of lubricant spinoff. Of particular interest is whether the model can be used in the parameter regime of concern in hard disk lubrication: polymeric fluid lubricants in films of the order of ten nanometers and smaller.

Polydimethylsiloxane (silicone) oils of two different molecular weights corresponding to kinematic viscosities of 0.1 and 1 cm^2/s at 25°C were obtained from Dow Chemical and coated onto single crystal silicon wafers of approximately 7.5 cm in diameter. The lower viscosity oil is composed of a polymer of approximately sixteen monomeric units, while the more viscous oil has about 81 units on average. Rodriguez (1982) presents structural data on polydimethylsiloxane from which we may estimate that the root-mean-square radius of gyration of our silicone oils are 7 Å and 16 Å, respectively, for the low- and high-viscosity liquids.

The initial coating was obtained by placing a puddle of about 2 cm^3 of oil onto the disk, and spinning this coating down to a uniform thin film with h_0 approximately 1 μm. Spinning was

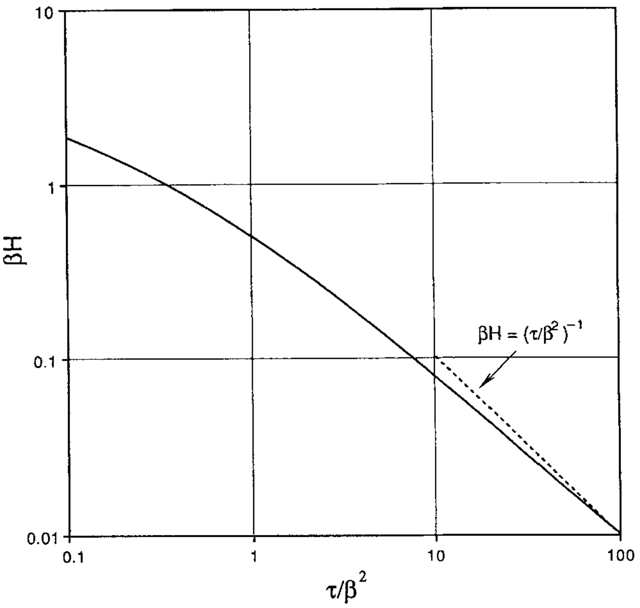

Figure 3. The function $H(\tau;\beta)$ from Eq. 4.

performed in a Headway Research PM 101 D Spin Coater. Initial and intermediate film thickness were measured using a Rudolph Research Auto El II autonulling ellipsometer. All experiments were performed inside a Modulair MS-100 laminar flow hood to reduce particle contamination.

Each reported film thickness is the average of individual measurements at nine positions on a disk: four points near the disk edge and four points at the midradius, ninety degrees apart, and one point at the wafer center. The fluid dynamic models, both the classical theory of Emslie as well as our wind-shear theory, predict that the film thickness should be independent of radial position. Our observations confirm this, and the variance of each set of nine data points is quite small.

Disks were cleaned with a xylene wash followed by a methanol rinse, and were dried by spinning in air. The surface was regarded as "clean" when ellipsometric measurement on a dry disk yielded a film thickness corresponding to the 30 Å native oxide layer on the silicon surface.

Although a clean silicon wafer is "mirror smooth," surface profile measurements were made in order to obtain a quantitative measure of surface roughness. These measurements were made using a Sloan Dektac 3030 Surface Profilometer and a typical profile trace is shown in Figure 4. For our silicon wafers, the centerline average amplitude over a length scale of the order of 1,000 μm was found to be around 2 nm.

Figure 5 shows a set of data obtained at 5,000 rpm, plotted as h *vs.* t, for the two silicone oils. Somewhere below $h = 1{,}000$ nm (1 μm) the film thickness begins to deviate from the classical theory of Emslie *et al.* and the data subsequently follow the wind-shear model very precisely, until the film thickness falls below 25 nm. At this stage the spinoff is retarded slightly. Virtually identical behavior is observed in a second set of data at 4,000 rpm (Figure 6).

Discussion

Despite its potential limitations, the simple wind-shear model predicts the film thickness *vs.* time behavior for h in the range from 1 μm to 25 nm. Ellipsometric measurement, based as it is on reflection of a light beam from two *parallel* surfaces, is not reliable when the solid substrate has a roughness comparable to the liquid film thickness. Hence we have chosen to present no data below a film thickness of 10 nm. A discussion of ellipsometry of rough surfaces by Vorburger and Ludena (1980) suggests that this is a reasonable precaution to take. We note further that the optical constants of very thin films differ from those in bulk films—another reason to exercise caution in reporting liquid film thicknesses below 10 nm, when they are measured by optical methods.

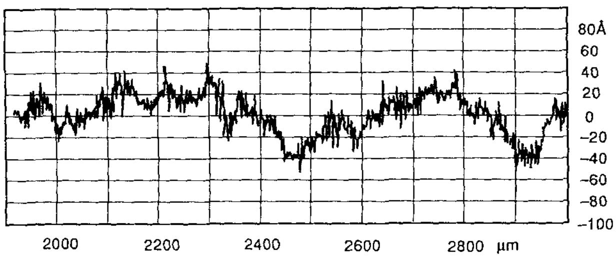

Figure 4. Profilometer trace across a silicon wafer.
Vertical scale expanded, relative to horizontal scale

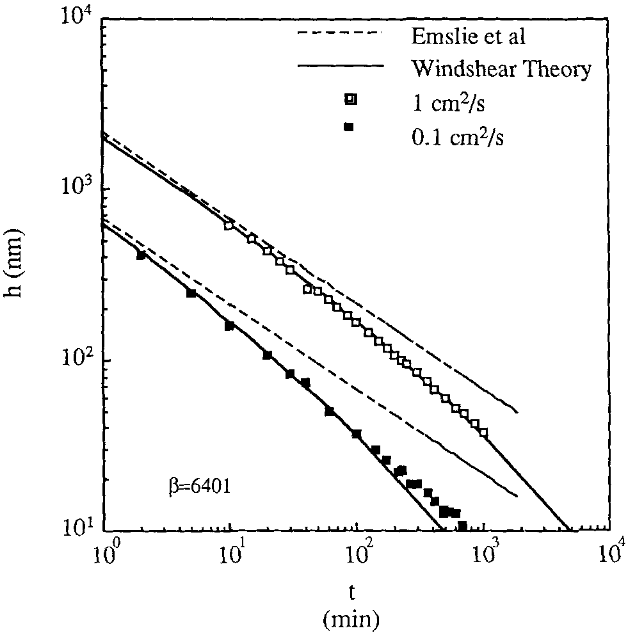

Figure 5. Data on $h(t)$ for two fluids at 5,000 rpm.

Our data indicate that, at least down to a film thickness of 25 nm, we can describe lubricant retention by using classical fluid dynamics. This is consistent with results reported by Israelachvili and Kott (1989), who find that the shear viscosity in extremely thin films is within 10% of the bulk value, down to film thicknesses as small as ten molecular diameters. The observation of retarded spinoff relative to the wind-shear model in the data in the 10 to 20 nm range is consistent with our expectations of the effect of surface roughness on film flow. Unfortunately, no quantitative model is possible at the present time with which we can offer a precise assessment of the effect of surface roughness.

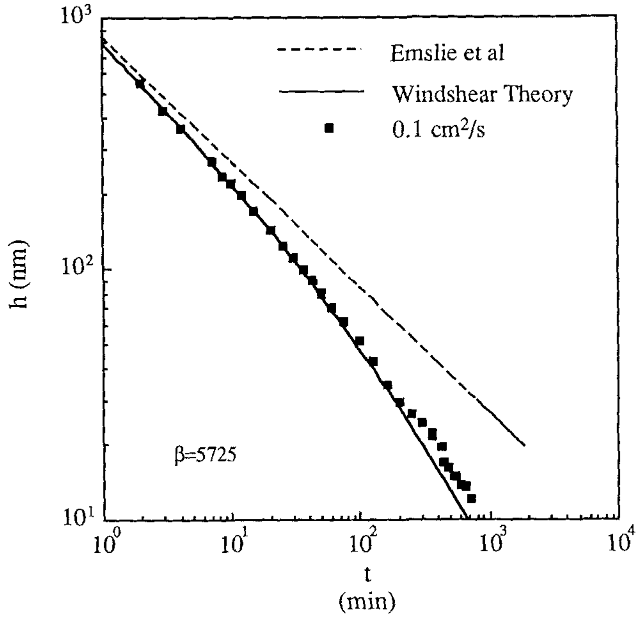

Figure 6. Data on $h(t)$ for 0.1 cm^2/s silicon oil at 4,000 rpm.

Finally, we note that there are reports of the investigation of "bonded lubricants,"—liquids believed to be covalently attached to the solid substrate. Studies with perfluoroether polymers by Barlow, *et al.* (1987) suggest that spinoff is retarded and possibly arrested by some (unknown) degree of bonding. This raises the issue of whether there is, within a distance of one or two molecular diameters from a solid surface, any difference between a liquid which is bonded to the surface, and one which "simply" satisfies the traditional no-slip condition at the surface. Such questions suggest and will require further studies along the lines of those of Israelachvili cited above.

Acknowledgment

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Notation

H = dimensionless film thickness, m
h = film thickness, m
h_0 = initial film thickness, m
N_{Re} = Reynolds number for the induced air flow
R = disk radius, m
t = time, s
T_{rz} = shear stress at the air/liquid interface, N/m^2
V_r = radial velocity, m/s

Greek letters

β = wind-shear parameter, Eq. 5
μ = liquid viscosity, Pa · s
μ_{air} = air viscosity, Pa · s
ν_{air} = kinematic viscosity of air, m^2/s
ρ = liquid density, kg/m^3
ρ_{air} = air density, kg/m^3
τ = dimensionless time, Eq. 2
ω = rotational speed, rad/s

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Errata

In the paper entitled "Local Turbulence Model for Predicting Circulation Rates in Bubble Columns," by K.G. Anderson and R.G. Rice (**35**, March 1989, p. 514), the first term in Eq. 17 should read $2 \cdot \Gamma/3$ rather than $2/3\Gamma$. This typographical error did not affect the computed results.